Battery characterization methodology for electric vehicles

by

Aarón Gutiérrez Fernández

Submitted to the Department of Electrical Engineering, Electronics, Computers and Systems
in partial fulfillment of the requirements for the degree of

Master's Degree in Electrical Energy Conversion and Power Systems

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Abstract

Since electro-mobility has increased in the last few years, it has become a source of research and innovation from universities to the industrial environment. One of the biggest problems that electro-mobility has to face according to progress is the energy storage problem. This thesis wants to contribute to electro-mobility improvement and the changeover of the concept of future mobility. The project will cover a general analysis of the electrical energy storage state-of-the art, the market and the technology of nowadays batteries for the automotive industry, the characterization techniques and the process. The first part of the work will analyze the state-of-art and the market of energy storage systems focused in batteries for automotive purposes and the electric vechicle. Then, an extensive testing sequence will be proposed in order to improve the electric vehicle battery pack knowledge. Furthermore, several characterization techniques will be explained and thorough test cases will be proposed, explaining the purpose of each tecnique focusing on the electric vehicle requirements. Finally, the testing setup and the automatization of the testing procedure will be considered.

Keywords: Electric vehicle, Battery characterization, BESS, Lithium-ion, Battery testing.

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Glossary

Ah Ampere-Hour – A unit of measurement of a battery's electrical storage capacity. Current multiplied by time in hours equals ampere-hours (Ah). One amp hour is equal to a current of one ampere flowing for one hour. Also, 1 Ah is equal to 1,000 mAh.

C C – Used to signify a charge or discharge rate equal to the capacity of a battery divided by 1 hour. Thus C for a 1600 mAh battery would be 1.6 A, C/5 for the same battery would be 320 mA and C/10 would be 160 mA. Because C is dependent on the capacity of a battery, the C rate for batteries of different capacities must also be different.

OCV Open Circuit Voltage: The difference in potential between the terminals of a cell when the circuit is open (i.e., a no-load condition).

SoC State of charge: Remaining capacity in the cell/ battery as a percentage of initial capacity.

SoH State of Health (SOH) – Remaining life time of the cell/ battery as a percentage of initial life time.

Acronyms

BESS Battery energy storage sytem.

BEV Battery electric vehicle.

BMS Battery management system.

CAES Compressed air energy storage.

DUT Device under test.

ECM Equivalent circuit model.

EIS Electrochemical impedance spectroscopy.

ESS Energy storage sytem.

EV Electric vehicle.

HESS Hydrogen energy storage system.

HiL Hardware in the loop.

HPPC Hybrid pulse power characterization.

IEC International Electrotechnical Commission.

ISO International Organization for Standardization.

LCO Lithium Cobalt battery.

LFP Lithium Phospate battery.

LMO Lithium Manganese battery.

LTO Lithium Titanate battery.

NCA Lithium Nickel Manganese Aluminium Oxide battery.

NMC Lithium Nickel Manganese Cobalt Oxide battery.

PHES Pumped hydro energy storage.

PHEV Plug-in hybrid electric vehicle.

PSB polysulphide–bromide flow battery.

PTC Positive thermal coefficient.

SAE Society of Automotive Engineers.

SLI Starting light and ignition.

SMES Superconducting magnetic energy storage.

TES Thermal energy storage.

USABC United States Advanced Battery Consortium LLC.

VRB Vanadium redox battery.

Chapter 1

Introduction

1.1 Motivation

Electrical energy storage is the biggest challenge faced by the electric energy industry. A feasible, reliable and real solution to store electrical energy would solve many problems related to green energies and electro-mobility. This could improve the human fossil fuel dependency and help in the battle against climate change. A suitable solution for the problem of electrical energy storage could boost the generation of green electricity, clean energy mobility and eliminate the highly nocive fossil fuels. This project wants to take place of this milestone and contibute to the improvement of energy storage. Since the automotive industry is a major consumer of fossil fuels, this problem shall be tackled. Nowadays, electric vehicles are improving and sales are increasing at a fast rate. To contribute to switch this mobility model towards a greener electro mobility system this project wants to propose several exhaustive test procedures in order to help researchs and companies to find and solve the problem of electrical energy storge in electric vehicles.

1.2 Objectives

The EV market is slowed down by the energy storage problem caused by the current battery pack technologies. To have a feasible product in the automotive industry market, the problem of the vehicle driving range should be solved. Ona Egbue et al. in [21] explain consumer's biggest concerns when buying an electric vehicle, which are the driving range, the car price and the charging times. To tackle this issue, the world needs big, reliable and cheap batteries, as well as powerful and fast charging infraestructures. Electric vehicles should have excellent energy storage methods so that they can be charged fast, in less than 30 minutes nowadays and, ideally, in the future, in 10 minutes, like the traditional combustion car. Furthermore, the battery pack should be able to store great amounts of energy, the neccesary to drive more than 500km. This work could help to improve one of those variables, the battery technology in this case, providing a better knowledge of the battery behavior and characteristics in different scenarios. These tests can help to provide a better idea of battery performance, working ranges, product characteristics and paramameters in order to improve the battery pack for EV. Further information and more realistic mathematical models of battery packs could be helpful for vehicle designers. Those designers could adjust the vehicle behavior to optimize the battery range and capabilities. In the other hand, several literature of cell characterization procedures with different techniques could be found, but in terms of battery pack characterization there is less information. This project will try to help the automotive sector with energy storage issue. In order to do that, this work wants to achieve the following goals:

- To study the state-of-the art, the status of the market and the tendencies of energy storage systems focused on battery energy storage for the electric vehicle/for electric vehicles.
- To evaluate different battery characterization procedures and asses which fits better to electric vehicle requirements.
- To define a valid testing procedure in different scenarios to characterize full battery packs systems according to automotive industry necessities.
- To design a valid laboratory setup capable of automatically executing the characterization test in complete battery packs.

1.3 State of the art

The electrical energy storage system have suffered a radical change for the better in the last few years. Nowadays, a great deal of different electrical energy storage systems can be found. This variety appeared due to market requirements and the need to store electrical energy in different sectors. Various forms of energy storage can be found, from pumped-hydro energy storage (PHES) to battery energy storage system (BESS) , going through compressed air energy storage (CAES) , thermal energy storage (TES) , Hydrogen Storage system (HESS) and flywheels.

Table 1.1: ESS characteristic comparison [13], [45]

Technology	Energy density (W h/L)	Power density (W/L)	Specific energy (W h/kg)	Specific power (W/kg)	Power rating (MW)	Rated energy capacity (MW h)
PHES	0.5–1.5	0.5–1.5	0.5–1.5	–	100–5000	500–8000
CAES	3–6	0.5–2	30–60	–	Up to 300	<1000
Flywheel	20–80	1000–2000	10–30	400–1500	<0.25	0.0052
Lead–acid	50–80	10–400	30–50	75–300	0–20	0.001–40
Li-ion	200–500	1500–10,000	75–200	150–315	0–0.1	0.024
NaS	150–300	140–180	150–240	150–230	<8	0.4–244.8
NiCd	60–150	80–600	50–75	150–300	0–40	6.75
VRB	16–33	<2	10–30	166	0.03–3	<60
ZnBr	30–60	<25	30–50	100	0.05–2	0.1–3
PSB	20–30	<2	15–30	–	1–15	Potential up to 120
Capacitor	2-10	100,000+	0.05–5	100,000	0–0.05	-
Supercapacitor	2-1010–30	100,000	2.5–15	500–5000	0–0.3	0.0005
SMES	0.2–2.5	1000–4000	0.5–5	500–2000	0.1–10	0.0008
Hydrogen Fuel cell	500–3000	500	800–10,000	500	<50	0.312
TES	200–500	-	80–120	10–30	0.1–300	-

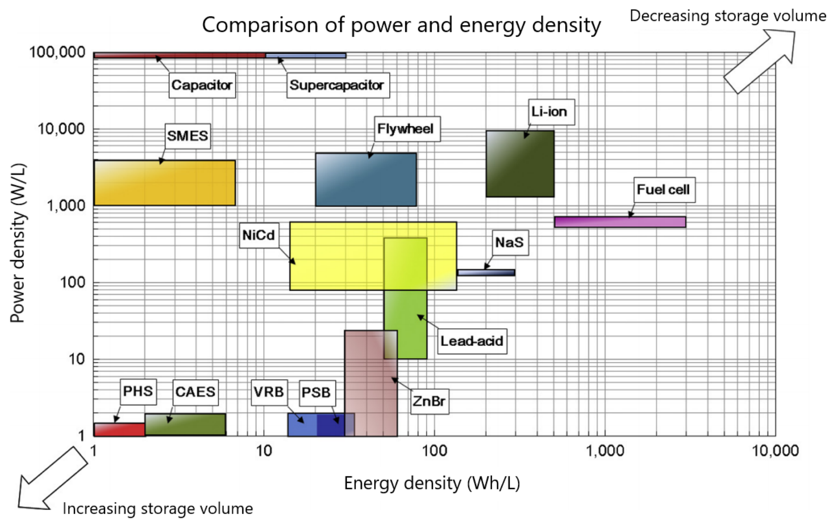


Figure 1-1: Energy and power density comparison [45]

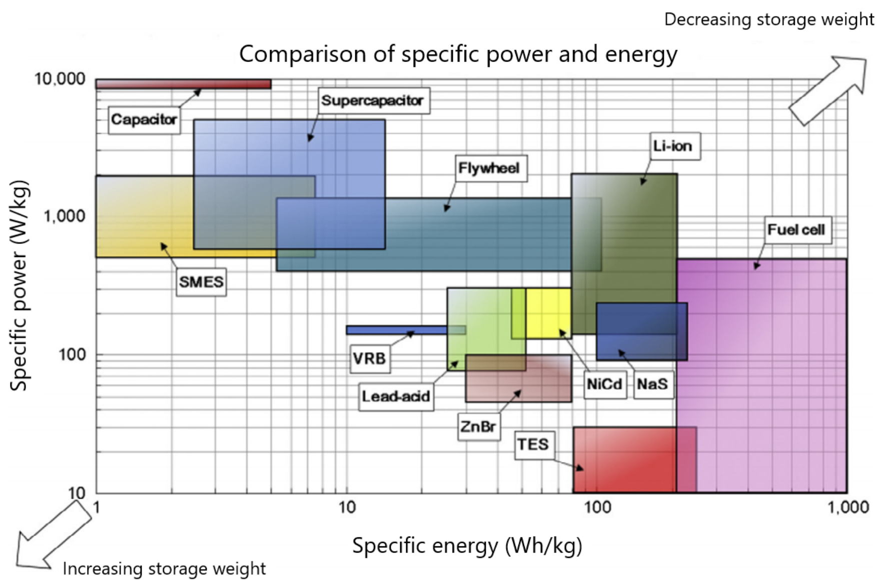


Figure 1-2: Specific energy and power comparison [45]

For the automotive sector, the most interesting ways of ESS are the BESS, such as lithium-ion batteries, nickel-based batteries or the hydrogen fuel cell, with a bright future in the automotive sector [23], but in an early state of industrial integration. Flywheels are a highly interesting technology for the automotive sector but, although some companies are researching about this type of energy storage, it still is at a first stage of development.

But, nowadays and in the nearly future the most matured and integrated technology in automotive industry is the Li-Ion battery technology, as it satifies all the automotive market demands such as excellent safety, high specific energy, high specific power, good temperature characteristics, long cycle life, low cost, no maintenance, low self-discharge, good consistency, no environmental pollution and recyclability. In Table 1.1 the Li-ion characteristics can be seen in comparison to other ESS technologies. Also, in Fig.1-1 and Fig.1-2 a graphical comparison of the different ESS is shown. Both figures prove that Li-ion batteries can provide a big amount of power for its size and weight, only overtaken by the Fuel cell, previously mentioned as a promising energy storage system in the long-term future. For all these reasons and the market cost reduction, Lithium-ion batteries are the perfect candidates to fulfill USABC requirements for full electric vehicles [59] as can be seen in Figure 1-4.

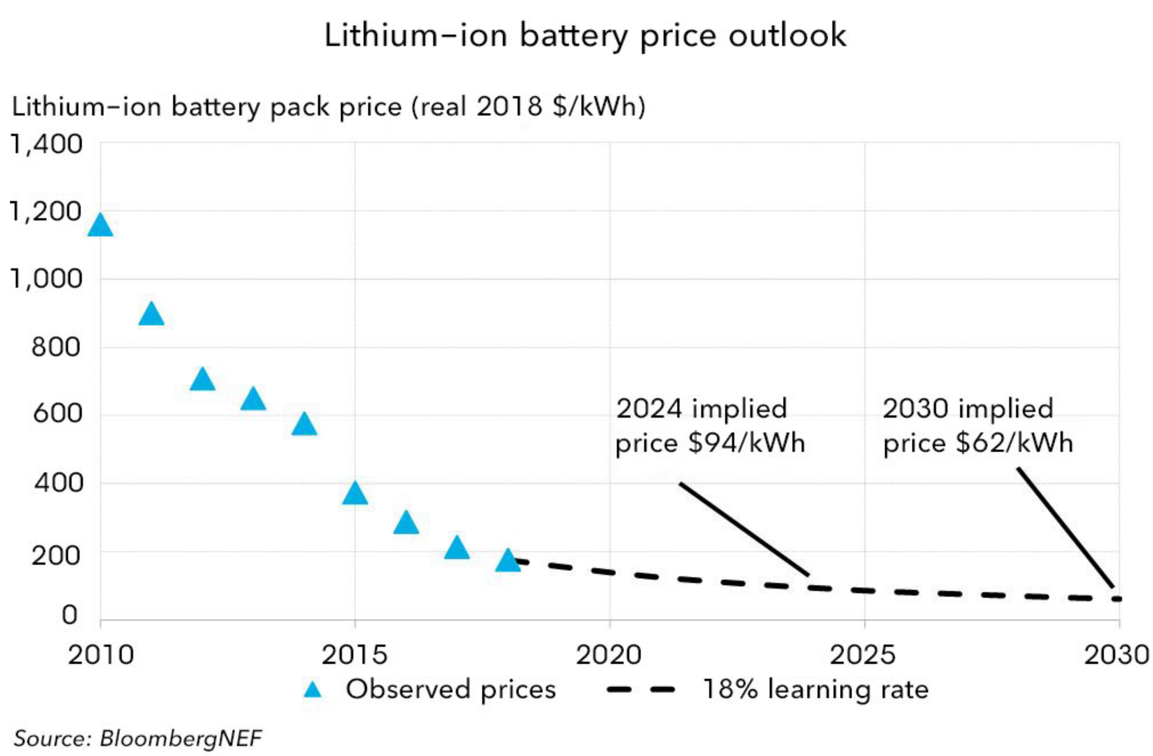


Figure 1-3: Price cost prediction from [25]

1.3.1 Automotive design criteria

The goals of the United States Advanced Battery Consortium (USABC) for BEV are 350 Wh/kg of especific energy at (C/3) rate, 750 Wh/L of energy density at (C/3) rate, 300 W/kg of especific power with a 10 s pulse, 700 W/kg of specific power with a 30 s pulse, a lifespan of at least 1000 cycles, an operating temperature range environment of −30 °C to +52 °C, a recharge time less than 7 h, a high-rate charge to 80% state of charge (SoC) in 15 min, a self-discharge rate less than 1% per month [51]. This definition is very clear and a good goal to fulfill. The USABC provides clear information about the battery pack future and goals.

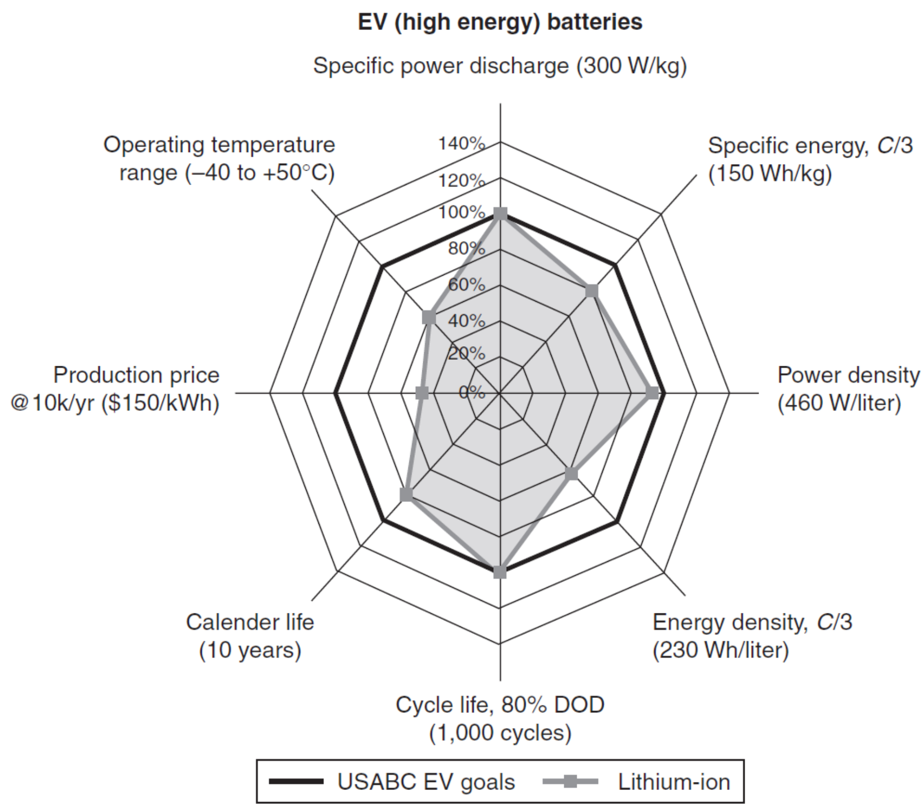


Figure 1-4: USABC targets [59]

Some research has been done about the ideal criteria for the electric vehicle,[41]. Also, some international regulatory committes want to define a routeplan for manufacturers and researchers in order to help to achieve the technology improvement. The European Commission's science and knowledge service provide some advice about the design and regulatory aspects in their technical report developed by Joint Research Centre (JRC) [62]. Some international organizations also provide design and testing advice, such as the IEC, with IEC 62660-1:2018[36] and IEC 60086-2:2015 [35], ISO with ISO 12405-4:2018 [37] and SAE with J1798_200807 [69] and technical papers [64], [3]. But since those pieces of advice and recommendations are not open access information they suffer from an accessibility issue.

1.4 Automotive BESS

Automotive manufacturers use different types of BESS. Nowadays, in market cars of automotive companies, the most common battery types are: Lead-acid batteries, use for starting, lighting and ignition, SLI; Nickel based batteries ($NiCd$, $NiMh$ and $NaNiCl_2$) that have several purposes in automotive sector, such as SLI, batteries for HEV or PHEV; and finally, Lithium-ion based batteries ($LiCoO_2$, $LiFePo_4$ or Lithium polymer), the main technology in the current EV market. Naturally, some other novel technologies are presently under investigation for automotive purposes, such as lithium based supercapacitors or metal-air batteries, However, these technologies are at first stage of development and therefore are not mature enough to be included in the manufacturing process [12].

Table 1.2: Automotive battery types

Application	Voltage [V]	Type
SLI	14	Lead-acid
Start and Stop	14	Lead-acid
Mild hybrid	48-200	NiMH
Full hybrid	300-600	NiMH
PHEV	300-600	Lithium-ion
BEV	300-600	Lithium-ion

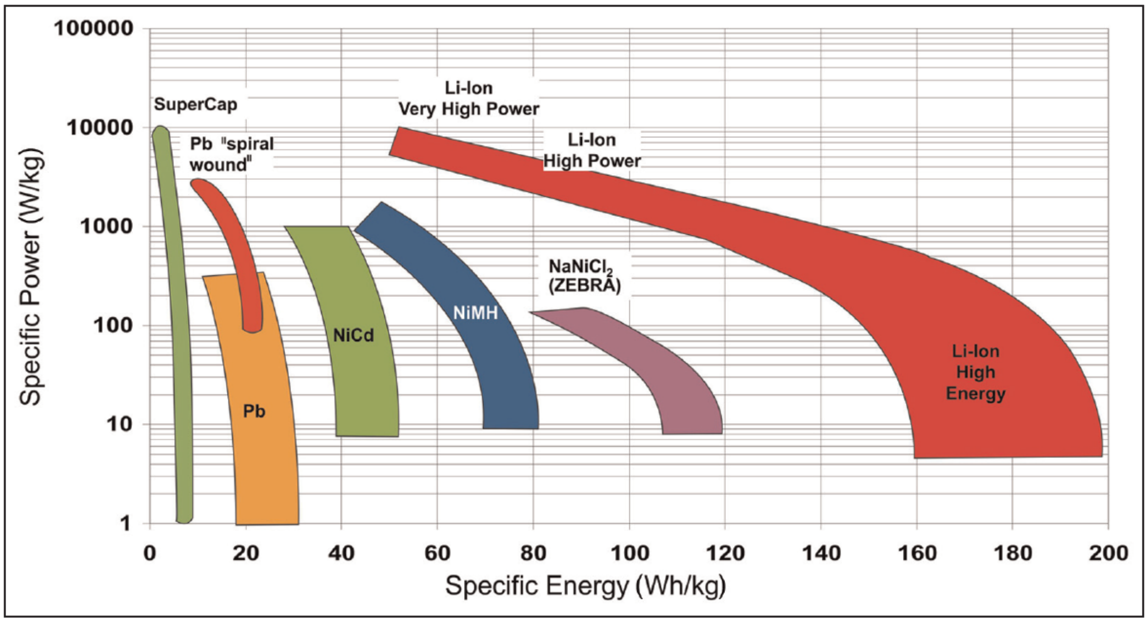


Figure 1-5: Ragone plot battery technologies comparison [12]

In the automotive sector, several different battery types exist. Starting with the most traditional lead-acid battery to help the ignition and cold cranking, and ending with the lastest technology, i.e lithium-sulfur battery. Lead-acid is commonly used to start the engine and power the electronic system with the engine off. Nowadays, this battery also appears on start-stop technology, a quite modern solution to reduce the CO_2 emmisions and to save fuel according to European regulations. Moreover the NiMH batteries appears with the full hybrid vehicle, such as Toyota Prius. It can run in EV mode (very short range) and save fuel in hybrid mode.

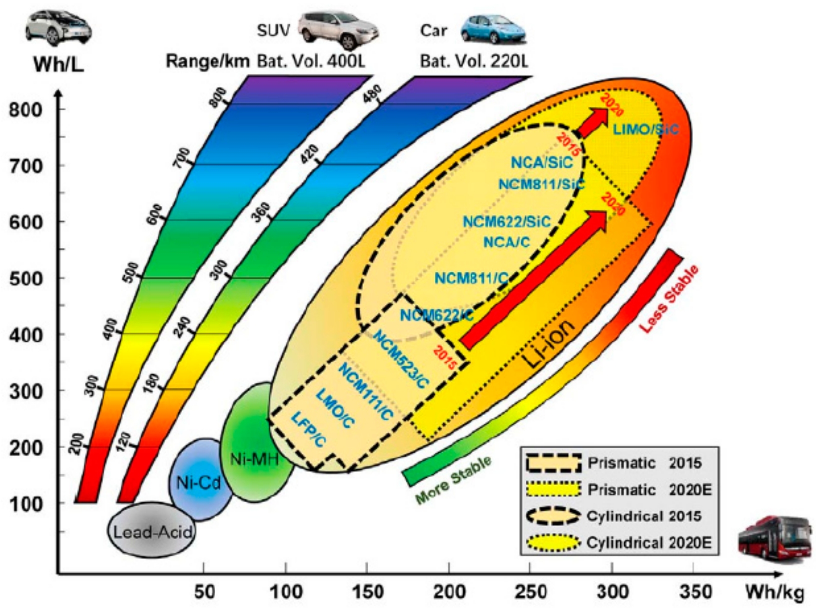


Figure 1-6: Automotive battery roadmap [2]

For this type of cars, more power and energy density than traditional for cars is a must. For this reason, manufacturers chose this technology for full hybrid vehicles. The next step of electrification is the PHEV. The emergence of these vehicles is considerably interesting in the present market, because hey are a transition from full hybrid concept to EV. Actually, it is a full hybrid vehicle with more range with a plug to charge the battery. These cars need same power as full hybrid, but they require more energy, so manufacturers decide to use lithium-ion batteries. These vehicles were thought to use the electric range on a daily basis and have more range for long trips.

Table 1.3: Comparison of automotive batteries characteristics [2]

Battery type	Energy density (Wh/L)	Power density (W/L)	Nominal voltage (V)	Life cycle	Depth of discharge (%)	Estimated cost (USD/kWh)
Lead-acid	50-80	10-400	2	1500	50	105-475
NaS	140-300	140-180	2.08	5000	100	263-735
NaNiCl	160-275	150-270	-	3000	100	315-488
NiCd	60-150	50-600	1.3	2500	85	-
VRB	25-33	1-2	1.4	13000	100	315-1050
ZnBr	55-65	1-25	1.8	10000	100	252-1680
Li-ion	200-400	1500-10000	4.3	10000	95	200-1260

Finally the EV arrives to automotive industry, and it needs to have much more energy. Since the only energy source is the battery, the EV needs to have a minimun range to satisfy daily conmutea and the range anxiety. 150km of range is more or less the number of kilometres that people are willing to accept for daily car use. Once this range is achieved, automotive companies could think about feasible products for the market. Definitely, these firsts electric cars are very far from the mass market. Now, the automotive market has changed a lot since the first modern concept of electric and hybrid vehicles surge. All regulations, the ecological concern with mobility and the market demands, have changed the routepath of automotive companies. Manufacturers have to adapt the product offers to satisfy these demands. Since the batteries are a key factor in EV development, companies invest a lot of money on this issue. One part of the project scope is to draw an overall picture of the most typical comercial batteries, but the project will put emphasis in lithium-ion batteries for EV.

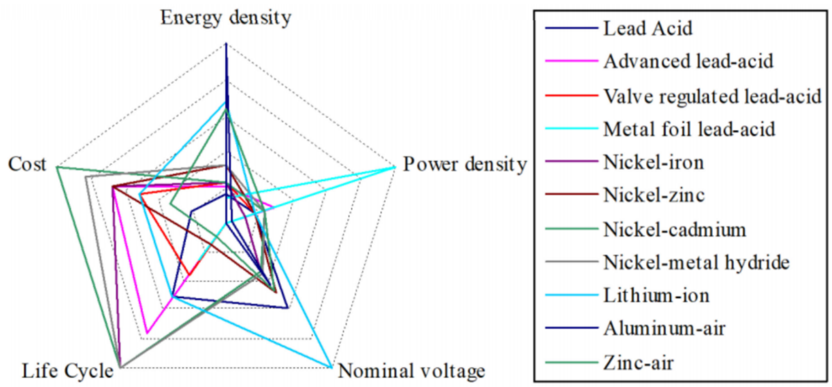


Figure 1-7: Spider chart of batteries technology comparison [2]

1.4.1 Lead Acid

Lead acid batteries are the most common batteries in automotive sector.Almost every car on the road these days has one of these batteries used to start the engine and the electrical system. This technology has an energy density between 30-50 Wh/kg and 2V per cell. The typical lead acid battery in a car works at 12V and can have different capacities (40Ah to 100Ah) and peak currents (400A to 1200A). These rates are related to the car manufacturing world, but these batteries are also used in trucks or other road vehicles. In these cases the battery will have greater working ranges. These batteries have some advantages, such as the cost (really low cost per cycle), the self-discharge rate, their high peak current, their easy reciclability and their temperature tolerance. The main disadvantages of these batteries are their low energy density, the short lifespan and the slow charge rates, [76], [12], [9].

1.4.2 Nickel based

During the 1990s, when the first ideas around EV emerged, automotive manufacturers chose nickel batteries to electrify cars. Therefore several types of nickel based batteries were investigated by automotive companies such as, nickel—zinc (NiZn), nickel—metal hydride (NiMh) or nickel—cadmium (NiCd). These batteries, also known as alkaline rechargable batteries, were interenting for automotive because of their properties, high power, wide operating temperature range (−30 to +70°C), safety and price. The NiMh battery became a boost for high power and wide operating range HEV. Nowadays, NiMh continues to be the most popular nickel-based battery for the automotive sector since its introduction to the market in 1996. From that point onwards around 6 million vehicles have been put in the road thanks to this technology. The general characteristics of these batteries are their flexibility during fabrication, that they do not require any maintenance, they can be easily recyled (with the expection of NiCd batteries as their recyclability is more complex) and they are environment friendly. However, they have some disadvantages such as their high self discharge rate, their low voltage per cell (1,2v), and the memory effect [42], [56]. Nickel-based can have a high specific energy rate from 50Wh/kg to 110Wh/kg. Depending on the technology and materials used, it can be fast charged in 1−2 hours and slow charged in about 15 hours. These are the general characteristics of nickel-based batteries, but nowadays the market leader of nickel batteries is the NiMh due to its overall performance, ecology and safety. Even though, for example NiCd has a longer life and lower cost.

1.4.3 Lithium-ion batteries chemistry types

At present, lithium-ion batteries can be considered the best feaseable option for EV and electromobility. These batteries are commonly used in portable devices such as laptops or mobile phones but, in the lasts few years, these batteries have gaining a lot of popularity in the automotive industry. Despite the cost, they have high energy density, long life expectancy and low self-discharging rate, key aspects for automotive designs. These batteries fit vehicles appropriately but, they must a good BMS to control the temperature, voltage, current and SoC in order to ensure the safety issues and battery life cycle. These aspects are incredibly important, as was mentioned before, because lithium batteries can suffer from serious damage if any of these variables goes out of control. The different cathode material gives the name to the different lithium-ion battery chemistries. The most typical are, Li-Cobalt(LCO), Li-Manganese (LMO), Li-Phosphate (LFP), Lithium Nickel manganese Cobalt Oxide

(NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA), and Li-Titanate (LTO). Several technologies realted to lithium-ion batteries are under investigation such as lithium-sulphur or lithium-oxygen, but, they still are at a first stage of development. Several automotive manufacturers use this type of batteries now, as can be seen in table 1.4

Table 1.4: Electric vehicles and its battery technology

Brand	Model	Type	Battery type	Energy (kWh)
BMW	i3	BEV	Li-ion NMC 333	22
Chevrolet	Bolt	BEV	Li-ion NMC	60
Nissan	LEAF	BEV	Li-ion LMO-NCA	24
Tesla	Model S	BEV	Li-ion NCA	85
Renault	ZOE	BEV	Li-ion LMO-NMC	26
Honda	Fit	BEV	Li-ion LTO-NMC	20

Lithium-ion batteries can have a gravimetric energy density from around 100Wh/kg up to 250Wh/kg (depending on the chemistry used and the fabrication method), high specific power from 760 to 1800 W/kg, and a feasible fabrication cost. Although lithium-ion batteries are more expensive than other technologies, they have a good price-quality ratio with characteristics such as, wide temperature operating range, fast charge, a high discharge rate up to 40C, and a long cycle life of approximately 1,200 cycles. Above all, all these numbers depend on the chemistry, the manufacturer and the construction. In the commercial market, lithium-ion batteris have the best relationship between energy density, power density, scalability and versatility. For all of these reasons, and, especially, for their fast response and their energy and power density, highly important features for the automotive industry, lithium-ion batteries are the best candidate to take part of an EV.

Li-Cobalt

The most popular technology in small devices is LCO batteries. The battery consists on a cobalt oxide cathode and a graphite carbon anode. During the discharging process, the lithium ions move from the anode to to the cathode. Inversely, the lithium ions go from the cathode to the anode when the battery is charging. The main problems of this battery is the short life span, its thermal stability, its limited load capabilities and cobalt avalability. Since these batteries present these issues, strict controls of the rating charge should be applied and they cannot be charge or discharge above their C rate. Manufacturers recommend rating charges under 0.8C for safety reasons, thermal runaway mainly. These batteries have 3.6V nominal voltage, around 200Wh/kg of energy density, between 0.7C and 1C rates (above rates could reduce the battery total cycles dramatically), and lifespan between 500 and 1000 cycles. All of these charactistics do not make LCO batteries highly interesting for automotive purposes. Even though the old Tesla Roadster [57] and Smart Fortwo electric drive have this type of battery [48].

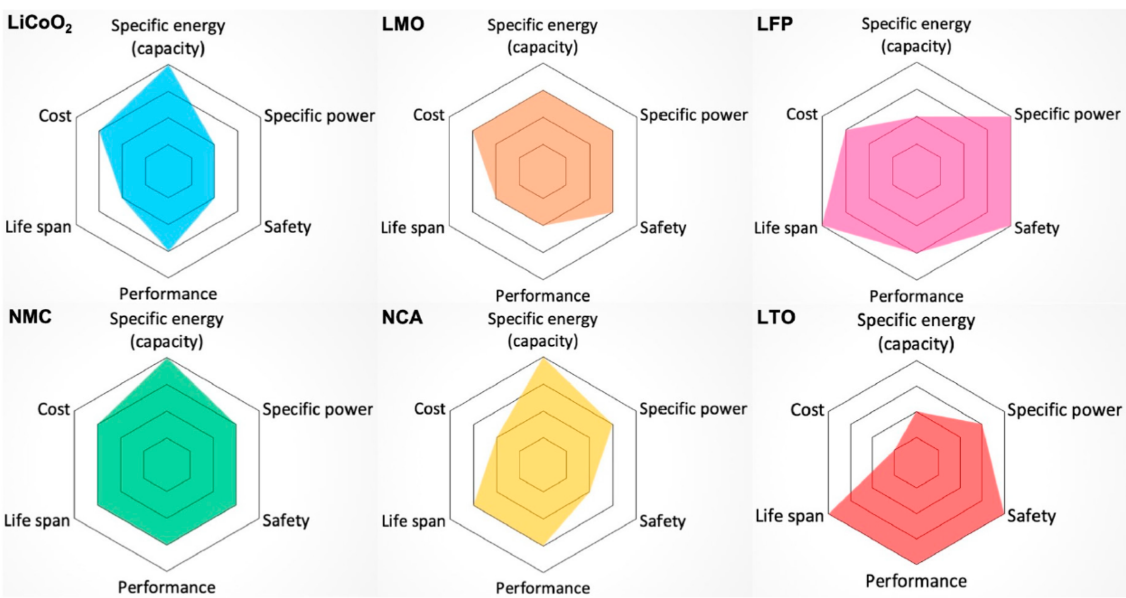


Figure 1-8: lithium-ion batteries cathode comparison [48]

Li-Manganese

$LiMn_2O4$ LMO batteries appeared around 1980 [75], even though these batteries required around 15 years to emerge into the market [73]. The use of spinel three−dimensional form improves the ion flow in the electrode and this provide to the chemistry low internal resistance and better current dynamics. A battery with low internal resitance can handle bigger amounts of current, and this will be reflected in a fast charge or discharge. Actually, these batteries are blended with other materials in order to improve certain characteristics such as the specific energy or the lifespan. Some EV manufacturers blend Li−manganese batteries with lithium manganese cobalt oxide batteries NMC to create a LMO−NMC battery. Manufacturers as Nissan in its Nissan Leaf, Chevrolet in the Chevy Volt and BMW in i3 use this type of battery[28]. The lastest research efforts to improve this technology come from changes made to the structure to obtain a better performance in capacity and C rate capability. These investigations are trying to develop a composite structure between spinel $LiMn_2O_4$ and layered $LiMn_2O_3$ [39]. These batteries can work at 3.7V nominal voltage and the operating range goes from 3.0V to 4.2V per cell. The specific energy can be around 100−150Wh/kg, they could charge at 3C maximum rate and can reach discharge rates from 10C to 30C in a short period of time. They can last for 300−700 cycles and they reach their thermal runaway at 250°C . The main drawback of these batteries is their capacity in comparison with other lithium-ion technologies and their limited potential growth.

Li-Phosphate

Lithium ferrous(II) phosphate ($LiFePO_4$) is a positive electrode material for lithium-ion batteries. This material was discover by Prof. John B. Goodenough and his group at the University of Texas in Austin, United States, in 1997. However, it was not very interesting until 2002 because it it could not deal with large amounts of current. In 2002, some techniques such as doping or coating improved the conductivity and its charge and discharge perfomance. The phospate increases the temperature tolerance of this battery, providing a wider temperature working range, from 60°C to −30°C. Moreover, it grants more resistance to thermal runaways to the battery. The self discharge rate is the main drawback of this chemistry due to the unbalancing with the aging. Nevertheless, this issue can be solved with advanced control electronics. Other bad constraints are the low capacity of the battery and its vulnerability against humidity, as it dramatically decreases the life expectancy of the battery [71]. These batteries have a typical operating range between 2.5V and 3.65V per cell and a very flat voltage discharge curve. The average energy density can be around 120Wh/kg. The typical charging rate is 1C and ($LiFePO_4$) they can reach dicharging rates up to 25C. They can last up to 2000 cycles or even more, depending on the depth of discharge and temperature. They reach the thermal runaway at 270°C. The average price of these batteries is $ 580 per kWh. All of these characteristics make these batteries ideal candidates for several applications, stationary, automotive or back-up power applications. Other good points of ($LiFePO_4$) are its very flat voltage curve and the safety. This technology has grown tremendously in recent years. Some example of vehicles that use ($LiFePO_4$) batteries could be BYD-E6 and Mitsubishi-iMiEV. The main manufacturers of this tehcnology are A123, BYD, GS Yuasa, SAFT, EIG, Lishen

Lithium Nickel manganese Cobalt Oxide

The main characteristic of this Lithium Nickel manganese Cobalt Oxide (NMC) is versatility. It can be a good candidate for either high specific power or energy [75]. Combininations between nickel cobalt and manganese can provide more especific energy, power or stability. In the one hand Nickel is well known for its especific energy and poor stability. In the other hand, manganese and its spinel structure has low internal resistance but low specific energy. Manufacturers are trying to reach the best combination for its applications, one typical conmbination is 1/3 of nickel 1/3 of manganese and 1/3 of cobalt. This combination is also known as NMC111. Battery companies combine these three elements in order to obtain the perfect battery depending on the application. This technology makes the battery very useful in several applications such as power tools, e-bikes and electric powertrain. The average operating range of this type of cell can be 3.0V to 4.2V. The common energy density ranges between 150-220Wh/kg. These battery cells withstand charge C rates up to 1C in normal working range and above 1C shortening they lifespan. The C rates of discharging go from 1C to 2C, until they 2.50V cut-off voltage. They can reach up 2000 cycles depending on the working conditions. These batteries are very safe and reach the thermal runaway at 210°C. The cost per kWh could be around $ 420. This chemistry is preferred by many manufacturers due to its capacity, power and versatility. In the case of NMC batteries, some EV model could be mentioned, such as Nissan Leaf, Chevy Volt and BMW i3 [28]. For instance, some manufacturers of these batteries are GS Yuasa, LG Chem, Samsung, Toshiba.

Lithium Nickel Cobalt Aluminum Oxide

These batteries, also called NCA are very similar to NMC due to their high specific, good specific power and long lifespan [48]. These batteries has been used since 1999 and they have small market share. The main drawback of this chemistry its the poor safety and it requires sophisticated electronics in order to be integrated in EV. Its usage flexibility in other applications and its manufacturing cost make this battery uninteresting to the market [48]. These baterries work between 3.0V and 4.2V per cell. They provide up to 300Wh/Kg of especific energy. They can charge at rates of 0.7C until 4.20V upper cut-off voltage and discharge rate up to 1C until 3.00V typical lower cut-off voltage. 500 cycles are the average lifespan and the thermal runaway is at 150°C. The average cost could be aproximatly $350 per kWh. Typical applications go from medical devices to indutrial applications and electric powertrain. Since they are used by Tesla through the manufacturer Panasonic, they have potential to grow up. As an example, some manufacturers could be mentioned, such as SAFT, Panasonic or AESC.

Li-Titanate

Lithium titanate oxide ($Li_4Ti_5O_{12}$), better known as LTO batteries, first appeared in the 1980s [84]. This chemistry replace the typical graphite in the anode of ion batteries for a spinel framework of titanate nanocrystals. This variant of anode provides to the battery with better performance in terms of high current capabity and flattens of voltage profile. The main advantages of this battery is the high current capability and thermal stability [68], but it has two important disadvantages: the price and the energy density. These batteries work between 1.8V and 2.85V per cell. They have

Table 1.5: Lithium-ion cathode technologies comparison

	Li-Cobalt	Li-Manganese	Li-Phospate	Li Nickel Manganese Cobalt Oxide	Li- nickel Cobalt Aluminium Oxide	Li-Titanate
Cathode chemistry	LCO	LMO	LFP	NMC	NCA	LTO
Specific energy (Wh/kg)	120-150	105-120	80-130	140-180	80-220	105-120
Energy density (Wh/L)	250-450	250-265	220-250	325	210-600	260-265
Especific power (W/kg)	600	1000	1400-2400	500-3000	1500-1900	1000
Power density (W/L)	1200-300	2000	1400	6500	4000-5000	4500
Volts (V) per cell	3.6-3.8	3.8	3.2-3.3	3.6-3.7	3.6	3.2-3.3
Cycle life	>700	>500	1000-2000	1000-4000	>1000	1000-2000

an especific energy density from 50Wh/kg to 80Wh/kg. One of the best features of these batteries is the C rate, 1C typical and 5C maximum rate of charging. When discharging, it is possible to reach 10C and, furthermore, it could discharge up to 20C in pulses. Their cycle life is another strong point of these batteries, as their lifespan can go from 3,000 to 7,000 cycles long. [81]. In thermal runaway terms, these batteries are one of the safest. The weakest point is that their cost could be of nearly $1050 per kWh. UPS, electric powertrain are typical applications for these batteries. To sum up, these batteries have certain advantages such as long life, fast charge and a wide temperature operating range. Their weaknesses are their price and their energy density. Some manufacturers of these batteries are Altairnano and Leclanché.

1.5 Lithium-ion batteries in EV

1.5.1 Lithium-ion EV cells

Three main types of cell can be detected in almost every segment of the automotive market. The different cells inside a EV could be cylindrical, prismatic or pouch. Certainly this type of cell are not exclusive for the automotive industry. Actually, the most widely used in EV is cylindrical type, due to its cost, safety, mechanical stability and reliability. The most common cylindrical cell is commercialized in 18650 packages. The name comes from its size, with a diameter of 18mm and a length of 65mm. Other formats can be found, such as the 20700, 21700 and 22700. These cells have an interesting safety mechanism, PTC switches to avoid overtemperatures and relais on a pressure mechanism to prevent explosions.

(a) Panasonic 18650 cell (b) Section 18650 real cell

Figure 1-9: cylindrical 18650 cell

The boom of these cells in EV arrived once Tesla started to use them in its vehicles [74]. This type of cells are used in several products, from laptops to electric vehicles. These cells are selected by Tesla because of their price, easiness of production and energy density. Despite their form, cylindrical cells can achieve much more energy than pouch or prismatic cells. Some manufacturers of these batteries are LG chem or Panasonic.

Nevertheless, prismatic cells have a more appropriate shape to be integrated in flat designs. These cells have a wound jelly-roll on their inside, with a flatter cylindrical shape and a hard case to protect it. The main advantage of these cells is the shape, the manufacturers can design the size of the cells so it fits in the desired application.

The final main cell form is the pouch cell, a very interesting design for the automotive industry. This type of cell is curious due to its flat form. These batteries are like a soft flat sealed package with two pieces of aluminum foil soldered to the anode and the cathode of the battery, as it can be seen in Fig.1-12. Pouch cells are slighty flexible and are the most efficient in terms of space user of cell types. A large

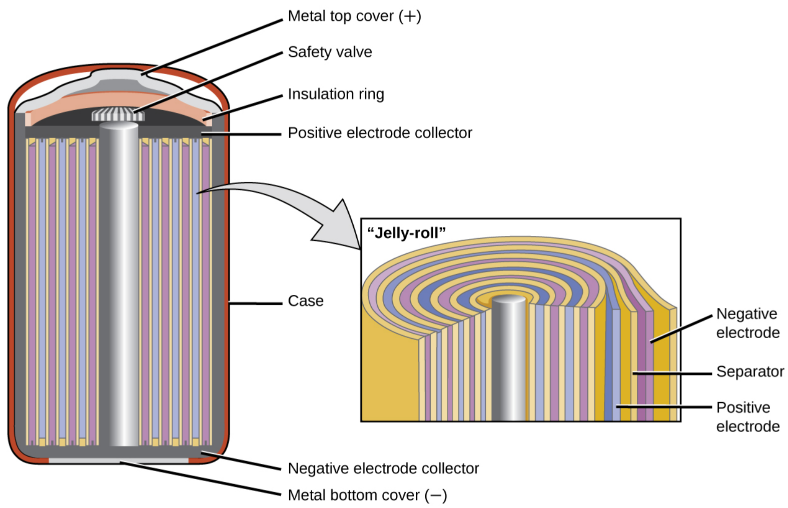
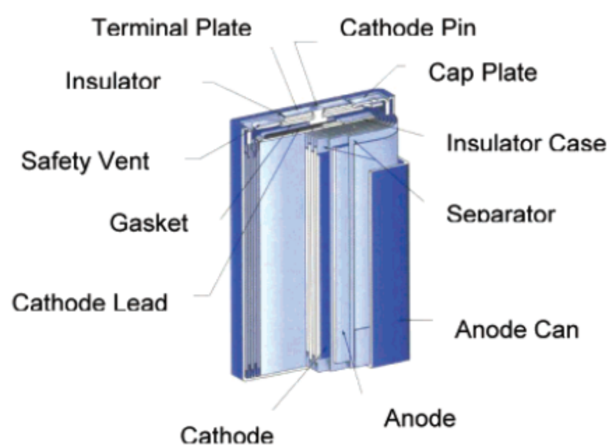


Figure 1-10: 18650 cell parts

(a) Commercial prismatic $LiFePO_4$ cell

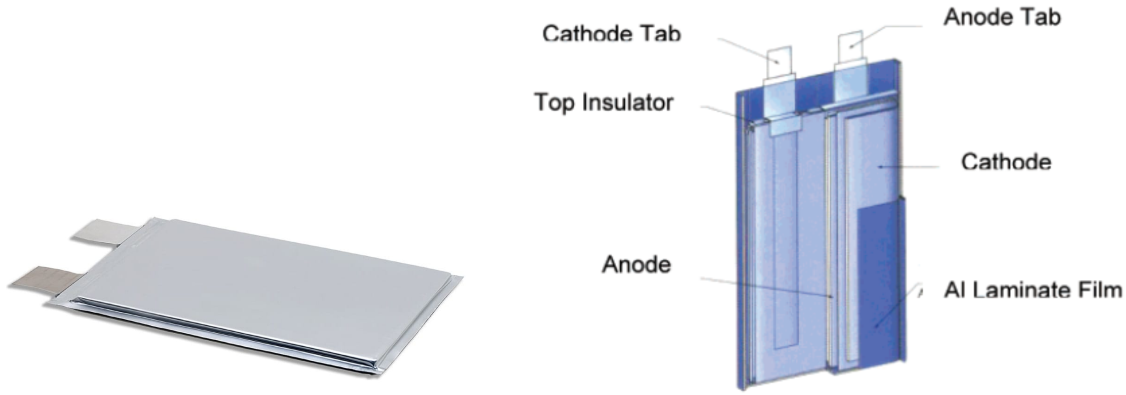


(b) Section of primatic cell

Figure 1-11: Prismatic cell

variety of sizes can be found in pouch cells, from short cells with high current deliver capability, to large cells for high energy density design simplification. These cell are stackable but need some space to to expand, due to internal pressure generated. These cells have a lot of options in the short term future battery package for automotive purposes. A suitable design can lead to interesting energy and power ranges. Automotive manufacturers such as Nissan in its 24kWh Leaf and General Motors in its 16.5kWh Chevrolet Volt use pouch cells.

In the table 1.6, a comparison between cell shapes can be seen [32]. This table



(a) Commercial pouch cell

(b) Section of primatic cell

Figure 1-12: Pouch cell

provide the manufacturer with information to choose one cell form rather than the others.

Table 1.6: Comparison of battery shapes

Shape	Cylindrical	Prismatic	Pouch
Electrode	Wound	Wound	Stacked
Case	Hard can	Hard can	Soft foil
Mechanical strength	Excellent	Good	Regular
Specific energy	Good	Good	Excellent
Heat radiation	Regular	Good	Good
Energy density	Good	Excellent	Regular

1.5.2 Automotive battery modules

To develop an automotive battery pack, the cells should be arranged in packets of several cells. The arrangement can be in series or in parallel to obtain the desired voltage and current capacity per module.

Manufacturers used to design these models to obtain low voltage ranges and a comfortable size for easy manipulation. Undoubtedly, each company has its own concept of design and can adjust it. The battery module provides a mechanical and fastening point to a group of several cells. These modules also have some space to place

Figure 1-13: battery pack design procedure

different types of sensors and safety protections. Usually, temperature sensors are placed in certain points of the module to prevent overheating and thermal runaways. Some manufacturers also put a current and voltage sensor per each small package of cells. Depending on the manufacturers, these modules could contain cooling system, BMS or other control and monitoring systems to supervise the important variables. All the modules must have the same size in terms of current and voltage, and have the same number of cells in series and in parallel. In the image 1-14 a commercial module of Tesla model S can be seen.

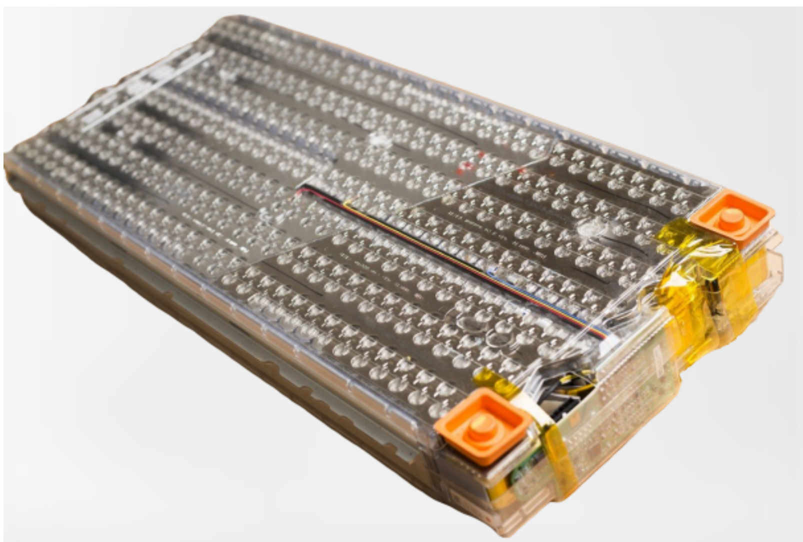


Figure 1-14: Tesla model S battery module

In this case, the module has some sensors, the power connection to the DC busbars, the racks are meant for connecting the pipes of the coolant system and a hard case for mechanical strength and support is implemented as well. Each module has a capacity of 232 Ah, works between 19V and 25.5V and which can deliver a peak of current of

750A during 10s.

Audi, for example, has chosen a different type of module for their e-Tron. They prefer pouch cell battery module, as can be seen in figure 1-15. These modules have twelve pouch cells each, stored in aluminium hard case, 4 in parallel and 3 in series. These modules reach 240Ah and 11V and they have temperature sensor inside the cage for each cell. In this case, the company chose a liquid cooling system placed in the battery pack floor to cool down the modules. Also, a battery module control unit is used in each the three modules to control the temperature of the cells, the voltage and the balancing.

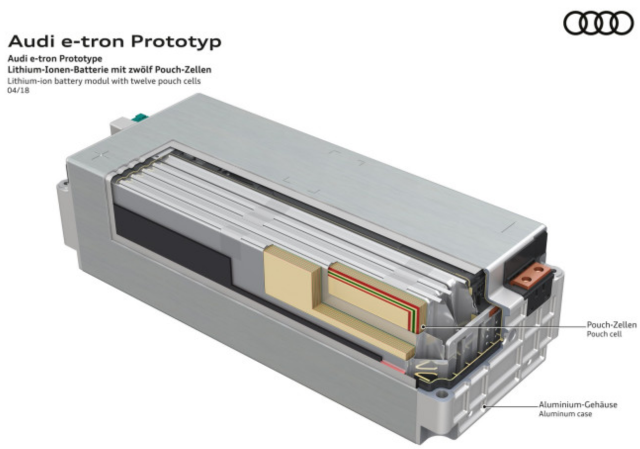


Figure 1-15: Audi e-Tron battery module

These examples showthe trend of auomotive industry in battery modules design. One company, relatively new, as Tesla and one with more automotive heritage as Audi, are trying to solve the energy storage issue in a similar way. The cells and the design are quite similar with slight differences in terms of final product, but having the same requirements.

1.5.3 Automotive battery packs

Once the battery modules and the space in the car designed for them are defined, the next step is to design the whole battery pack. A battery pack usally has and upper and lower case to store all the modules and electronics related to the battery. The lower case is mainly focused on structural support and protection of the modules. The upper case is focused on personal protection and on contact avoidance. It also provides fire protection and a dirt shield. This battery pack also contains electrical elements, such as contactors to isolate the battery, busbars to interconnect or fuses. The BMS usually goes in that battery pack too. Depending on the vehicle characteristics, such as size, segment, power, range and other features the battery pack can be extremely different from one car to another. However, all the EV battery pack systemsof different cars shares some characteristics between them, for example the energy density or the charging capacity. In this section a section, a set of battery packs will be explained to show the present status of the automotive market.

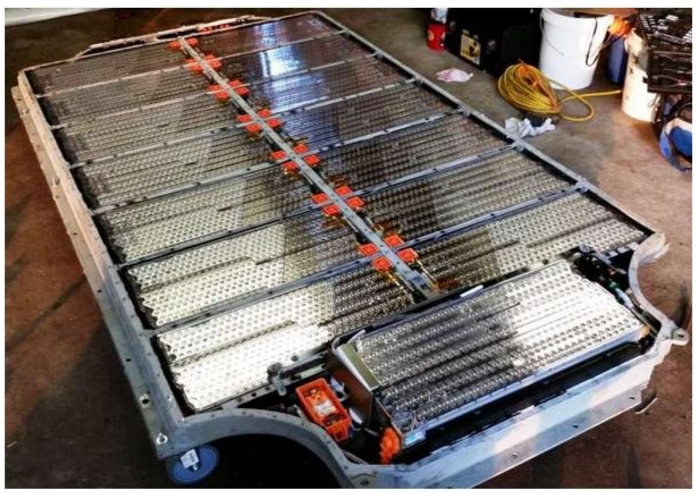


Figure 1-16: Tesla model S 85kWh battery pack

The Tesla battery for its model P100D has 96 cells in series and 86 in parallel. It works at 345V of nominal voltage. The battery can deliver 311kW as continuos peak power or 451kW peak power for only a few seconds. The energy of this battery pack is 100kWh, giving its name to the model. The weight of this battery pack is nearly 700kg and the especific energy is 149.3 Wh/Kg. In Fig.1-16, a Tesla battery pack can be seen. Tesla puts these final battery packs inside the floor of the vehicle. Another premium car battery pack is the Audi e-Tron. In this case, the company provides further information on how the battery pack is constructed.

This battery pack works with a nominal voltage of 396V. It contains 16 modules

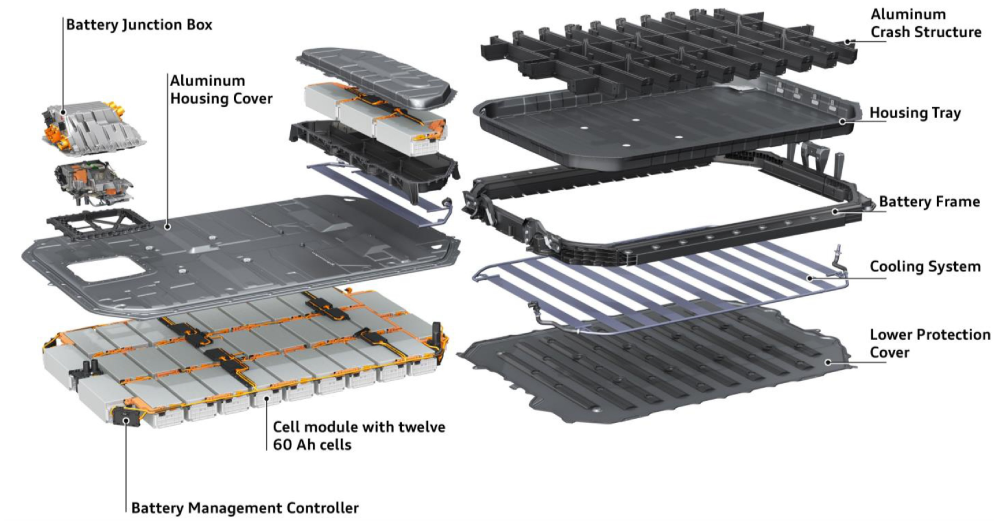


Figure 1-17: Audi e-Tron battery pack

with 516 cells in each module and has an energy capcity of 95kWh. It could reach 150kW when charging. Its weight is relatively similar to the one in Tesla´s Model S, 700kg. In this case, the cooling system consist on liquid coolant around the whole battery pack. Also, non-premium car manufacturers have EV options in their product portfolio. Companies such as Renault or Peugeot have EV models, such as Renault´s Zoe and Peugeot´s e-208. Other mass market EV is the world famous Nissan Leaf. In this case, the characteristics of the battery pack in the Renault Zoe will be explained in comparison with the Tesla model S and the e-Tron battery packs. The Renault ZOE Z.E 40, the second generation of this model, has been released in October 2016.

Figure 1-18: Renault Zoe battery pack

It has a battery pack of 40kWh and a weight of 305kg. It consist on 12 modules that contain, 192 cylindrical cells. The battery pack is placed in the car floor and has an air convection cooling system. It can deliver a continuos power of 65kW with power peaks of 88kW. It can charge up to 63 A with DC fast charging. This city vehicle has a range of around 300km.

Chapter 2

Characterization process

This project focuses on covering the characterization process for battery packs in the automotive industry. Since energy storage systems are quite different depending on the final application, this work wants to concentrate on the characterization for electric vehicles. Within automotive industry, several applications can be found in terms of electric transportation. From small city electric or hybrid cars to heavyweight transportation vehicles such as electric trucks or electric buses. The scope of this project is to draw the characteristics of the battery for compact and medium size passenger electric vehicles. Some examples related to this vehicle size connected to the project would be a number of cars of segment C, such as Volkswagen eGolf, Nissan Leaf, Tesla Model 3 or bigger cars of segment D like Tesla model S, Tesla model X, Kia e-Niro or BYD Han EV. These vehicles aim to achive more or less the same goals with similar characteristics. However, several differences can be found between Tesla Model X and Nissan Leaf, such as power, range , size or target client. But despite these differences, they could be in the same market portion, feseable passenger EV for mass market. In table 2.1 a comparison between the main characteristics of the different cars can be seen.

Table 2.1: Actual electric vehicle overview

Brand	Model	Battery energy (kWh)	Driving range (km)	Motor power (kW)	Charging time up to 80% (DC Fast charging)	Charging time 0%-100% (Slow charging)
Volkswagen	eGolf	35.8	200	100	34 min	5h-15h
Nissan	LEAF	62	363	160	30 min	10h
Tesla	Model 3 Long range	75	498	188+147	33 min	4h-14h
Tesla	Model S 100D	100	595	375+193	40 min	5h-17h
Tesla	Model X 100D	100	465	375+193	40 min	5h-17h
Kia	e-Niro	64	455	150	54 min	9h
BYD	Han	76.8	605	163	25 min from 30% to 80%	-
BMW	i3	33	183	125	41 min	4h-15h

2.1 Introduction to characterization

In the dictionary, to characterize means to describe someone or something as a particular thing. In this case, the characterization process in intended to describe the battery behaviour in certain scenarios. To characterize any entity, firstly, the desired parameters and the main goal shall be defined, in order to understand how it can be achieved. A main goal should be defined to know how can be reached. In this project, the objective is to propose characterization process of a whole battery pack for an EV. To know the parameters, investigations regarding the needs of the automotive sector and of the battery EV in particular were performed. The needs of this type of vehicles are crucial to identify the parameters to be extracted through the characterization.

An energy storage system, in this case, a BESS can be characterized for several purposes or sectors. The characterization will be different if the battery is a single cell or a pack of several cells. The main objective of this systems is to store electric energy in different forms, but the size and necessities could be really different deoeding ont the final application. Within the scope of the project, the characterization of a whole battery pack will be further explained.

Usually, a battery characterization process is performed to obtain some interesting static and dinamic behaviours. This process could be used to describe how the battery behaves in different conditons or to develop mathematical models for control or simulation purposes. In general, the most important characteristics in a battery are its voltage, current, energy and power ratings, plus its performance depending on temperature. As mentioned before, the goal is to describe how these different parameters work under certain conditions, either dynamic or static. This characterization process will propose the use of different techniques in order to obtain a deep knowledge of the battery pack behavior. To undersatnd the voltage battery behavior with remaining capacity, a curve that represents the voltage value versus the state of charge of the battery is usually characterized. In terms of current, how the battery behaves when facing high amount of current, both in charge and discharge, is commonly described. Moreover, the amount of energy the battery can deliver or or the amount of power it could handle are highly interesting in a BESS and, therefore, will be analyzed in capacity and power tests. Another interesting point is how the battery behaves under changing conditions. To analyze that dynamic performance different tests involving the dynamics will be proposed. Finally, the battery behaviour under different thermal conditions is an interesting aspect to understand the battery performance with thermal estress.

2.1.1 Open circuit voltage

This work will cover the open circuit voltage versus the state of charge performance. This battery pack feature try to show the evolution of the battery voltage without load against the actual SoC of the battery. Lithium-ion batteries have a quite flat voltage shape (between 90% and 10% of state of charge), and two agressive slopes in both ends. As can be seen in fig.2-1 [30] the voltage also increases with the SoC. Often, this OCV is a reference to know the SoC to BMS and the lower cut-off and upper cut-off voltage. This curve suffers from some variations depending on the environment variables and the aging of the battery. The shape is different if the battery is charging or discharging, and it may vary with temperature and if the battery is old too. This graphic shows a estatic battery measure that could be used as a starting point SoC when the battery is turned on. Furthermore, the SoC is a good indicator to know when the battery is fully charged or dicharged.

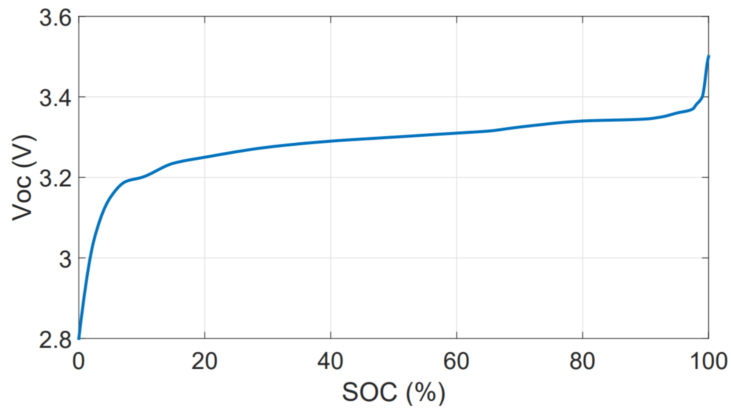


Figure 2-1: Lithium-ion typical SoC curve

2.1.2 Capacity

The capacity test aims to know the amount of energy that the battery has. This characteristic could be drawn from different C-rates and environmental variables. Temperature and environmental conditions will usually appear during the testing and characterization process. Batteries are strongly affected by external conditions. For the energy assesment, several method could be used [85], [54], but the most conventional and easy method to analyze the remaining energy in the battery is the coulomb counting method. Another interesting and reliable method is the discharge test under several controlled conditions. This test would be highly beneficial is there is enough time to perform it.

$$SoC = SoC_0 + \frac{1}{C_N} \int_{t_0}^{t} (I_{batt} - I_{loss}) d\tau \qquad (2.1)$$

Figure 2-2: Coulomb counting equation

2.1.3 Electrochemical impedance spectroscopy

Electrochemical impedance spectroscopy, also knows as EIS is a method to see the dynamic response of the battery at different frequencies , [58], [10]. With this method the behavior of the battery according to different frequencies can be draw in a graphical way through a nyquist plot. The idea of this test is to inject a small sinusoidal

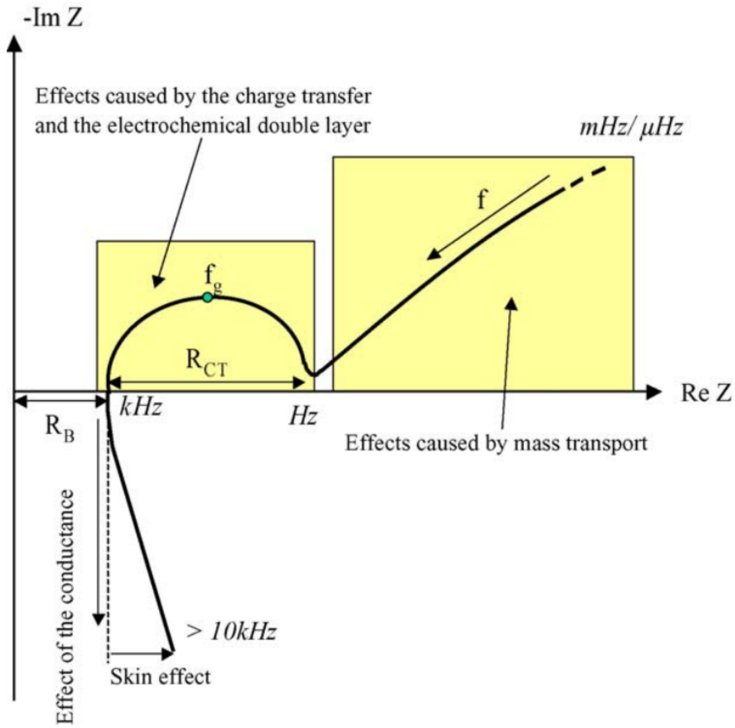
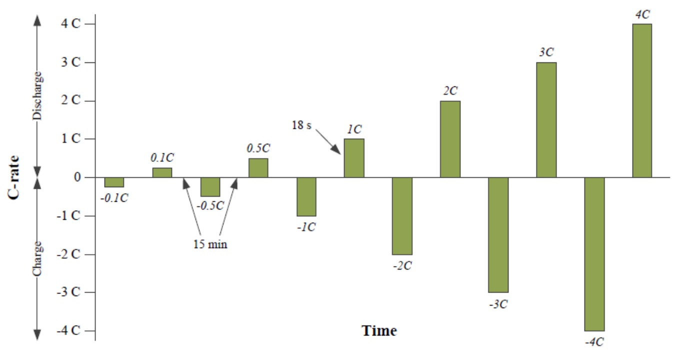


Figure 2-3: Typical nyquist plot

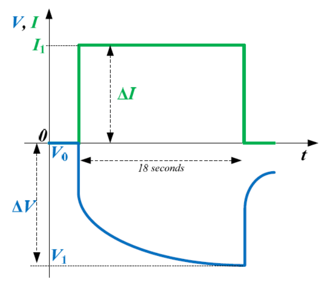
signal, which can be either a current signal (galvanostatic) or a voltage signal (potentionstatic) [4]. With EIS characterization, procedure information about the internal impedance can be obtained in a wide frequency range. Different physical effects can be noticed, such as mass transport, the electrochemical double layer and simple electrical effects. This test provides important information about the aging stage and the impedance dynamic behavior [50]. In Fig.2-3, a typical dynamic response of a battery can be observed [40]. Note that since the impedance is mainly capacitive the vertical axis is reversed to see the response in the upper side of x axis. As other characteristics, this test depends on external conditions such as temperature [14], [44] or on internal such as SoC. This process is widely used in the scientific world for battery characterization [20], [49], [46], [58].

2.1.4 Hybrid power pulse

The hybrid pulse characterization test provides information about the dynamic performance to high current load pulses to the researcher . This characterization consists on a series of current pulses of different magnitudes along all the SoC range. The test will be performed with different current discharge pulses together with some relaxation periods. Important information about how the battery behaves under short periods of high current stress and dynamic resistance will be obtained. Madani et al. explain the variation of series resistance in [47].



(a) Pulse profile example



(b) Singular pulse

Figure 2-4: HPPC Test

These characterization procedures are the the most common ones in order to have a basic knowledge of the battery dynamics. Thanks to these tests, general information about battery pack response to fast changes of current demand can be perceived. Information that can vary widely in the same battery pack with different initial conditions such as age , cycling, real operating voltage, current ratings of charging and discharging, actual values of power and energy rating, thermal performance, internal resistance or SoH. A variant of this characterization process would be testing under different real driving environments. Actually, real driving environments are a pulse power characterization with faster transients and lower C rates.

Depending on the application or on how deeply the battery should be analyzed, more tests could be added. For instance, in the scope of the project, another test under real driving conditions will be added to the analisys of the battery.

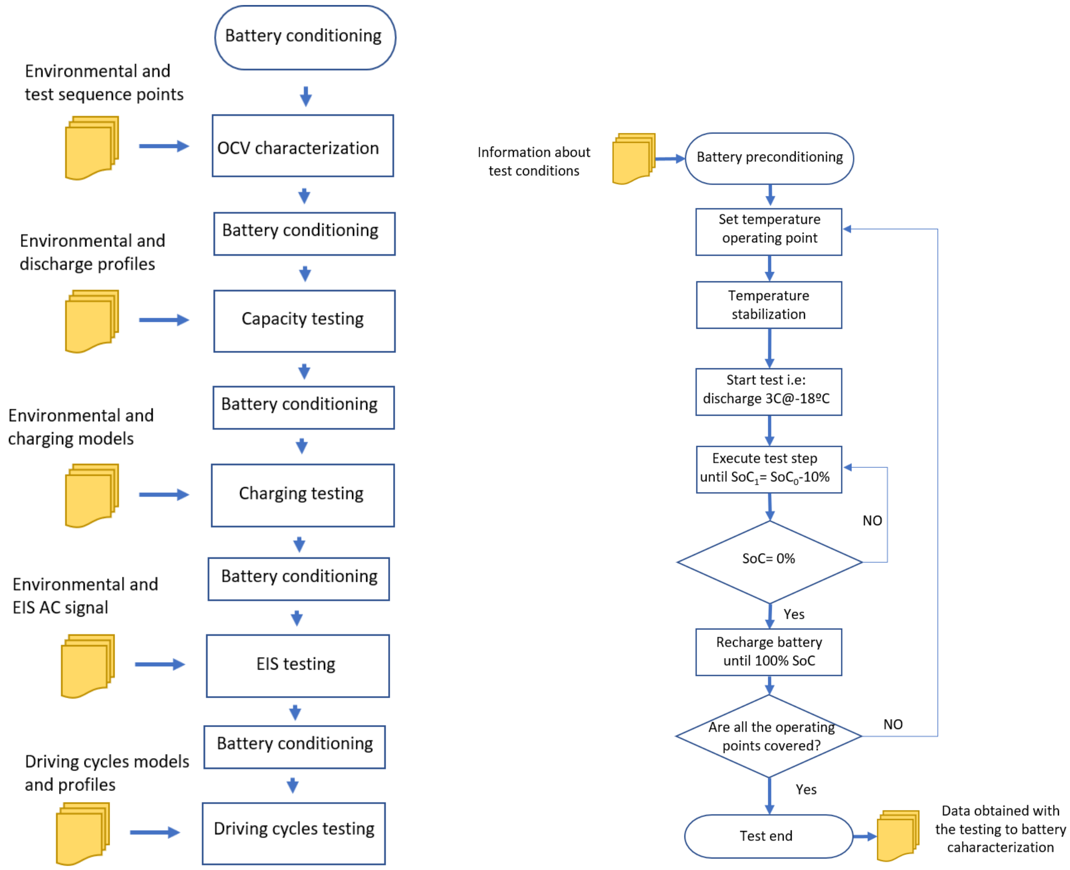
Table 2.2: Review of general characterization test

Test	Description	Purpose
OCV	consecutive measures of voltage in open circuit of the battery while slowly discharging	Characterize the OCV behavior versus SoC
Capacity	Discharge the battery under different conditons	Know the battery energy under different conditions (T, C-rate, kW)
EIS	Inject small AC current signal with wide frequency range at different SoC levels	Extract the internal resistance impedance information
HPPC	Discharge and charge the battery with succesive short time current pulses and increasing the pulse magnitud	Known the battery dynamic reaction to different current rates
Charge/discharge	Discharge and charge the battery with different current rates	Known the battery reaction to different charge methods and discharge intensities
Driving cycles	Discharge the battery under different real environment driving cycles	characterize the capacity and range according to different driving cycles

2.2 OCV characterization testing

The purpose of OCV characterization is to do several tests of the OCV vs SoC curve with small steps of SoC, different current ratings and with different temperatures of the operating conditions. Present regulations make some recommendations about temperature performance and manufacturers have their own standards as well. Nevertheless, no regulation regarding the temperature working range exists in terms of powertrain battery pack. Analyzing the manufacturers standards and ISO, IEC, SAE and other regulations, testing between -18°C to 60°C in steps of 10°C to 60°C will be proposed.

Usually, the car and the battery will operate under narrow working ranges, but a wider range will be interesting to explore feasible extreme working conditions. Moreover, thanks to this test, further information about the best temperature performance in



(a) Test characterization process (b) Example of test execution process

Figure 2-5: Flowcharts of characterization process and testcase

terms of SoC can be drawn. For the automotive sector, this characteristic is crucial due to the high thermal estress that the battery experiments inside the final vehicle. Also, controlling the temperature and working with the optimal operating point, could extend the range and the life of the battery. With this characterization the cut-off voltage to the fuel gauge will be obtained. As well as the upper cut-off voltage to the on board charger to not overcharge the battery could be defined too. Furthermore interesting behavior is the SoC prediction, with this test could be analyze the starting point of remaining energy.

The OCV vs SoC regarding temperature dependence when charging, which can be seen in Fig.2-7, aims to be a testing closely related to references [86] and [87]. However, the goal of this project is to design a test to cover the behavior with more resolution and a wider temperature range to ensure that the battery works perfectly in every

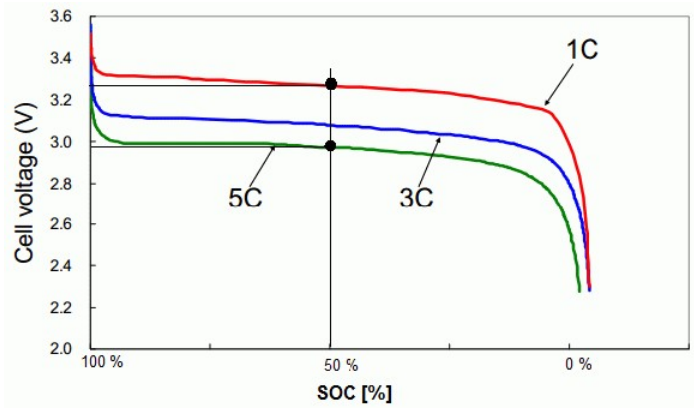


Figure 2-6: OCV VS SoC at different discharging currents

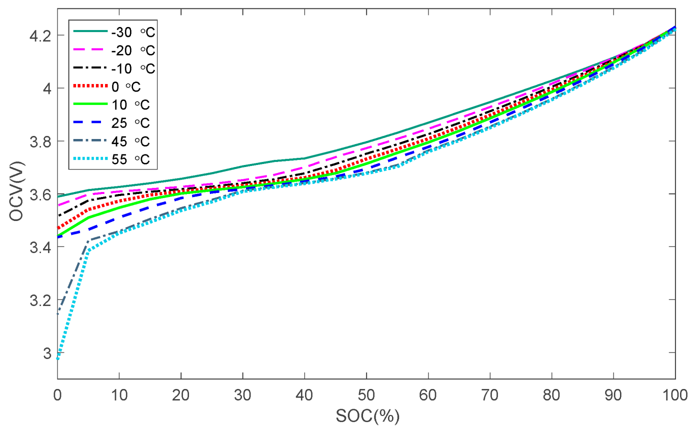


Figure 2-7: OCV VS SoC at different temperatures from [87]

real world scenario. Note that the reference mentioned analyzes the OCV curve only for one cell. The purpose of this work is to analyze the performance of a whole battery pack, that can vary from one battery pack to the same model battery pack of a single manufacturer due to cell dispersion. In this case a testing of a battery similar to the one used in Tesla model S P100D will be introduced. The OCV vs SoC different charging and discharging rates are suitable for the automotive industry too as it is crucial to know when the car should stop charging at certain rates or to control the current deliver to the motor.

In Fig.2-8 the variations at different rates can be noticed. In this case, they are seen from a cell analyses perspective as well [60]. For a final product, the whole battery pack will be more consistent than a unitary cell testing as the battery pack will be integrated inside the vehicle. Due to the high dependence of charging and

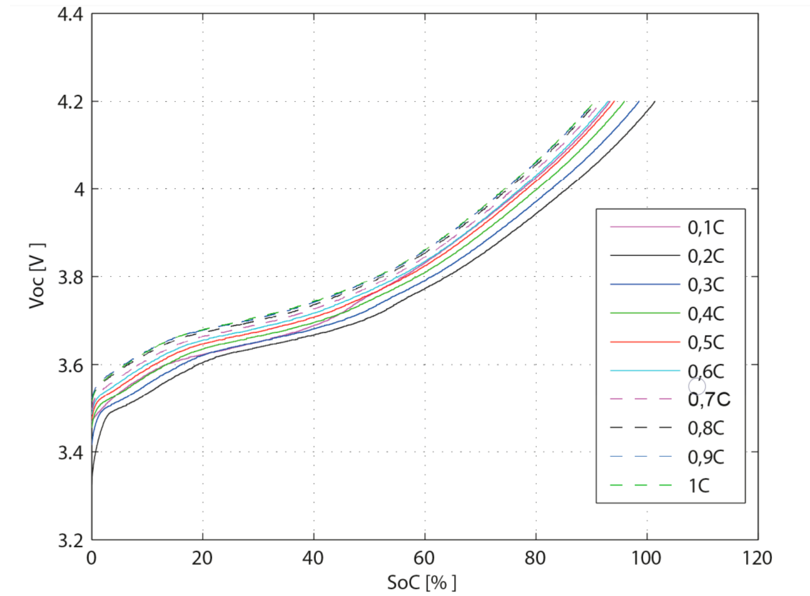


Figure 2-8: OCV VS SoC at different charging currents

discharging current and the operating temperature of the battery pack, [22], several operating points will be recommended to have exhaustive battery pack testing. To obtain the OCV vs SoC vs T for charging, the most conventional charging rates will be selected. In case of Tesla model S, the car could be charged at 3.7kW, 7.2kW, 22kW, 50kW, 150kW and, in nearly future, 200kW.

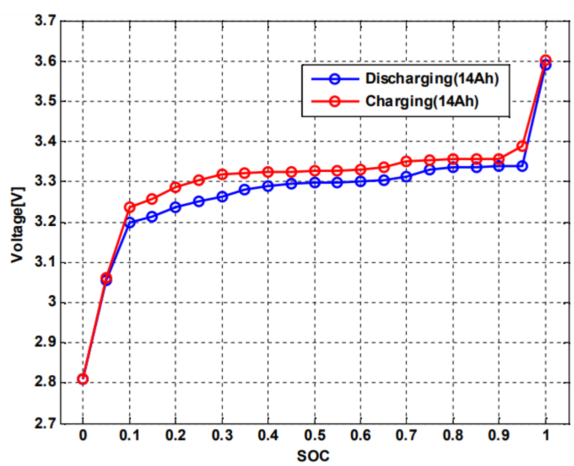


Figure 2-9: Hysteresis effect in battery charging and discharging

Furthermore, some researches comment on charging methods and powers in [17]. The car can work with powers up to 450kW in 3 seconds or 350kW continuosly. These two operating points should be tested for the dicharge curve. Another discharge curve would be the one of low current discharge. Finally, an OCV curve at continous motorway power will be drawn. In Tesla model S, users report an average power consumption of 20kW in a flat road at motorway speed. The OCV characterization shall be done in charging and discharging behaviors since the batteries present some hysteresis effects and round trip losses [7], [53].

- Battery preconditioning: Charge battery pack a 1C until 100% SoC at 25°C and let battery pack relax 3h. Execute only once before testing.
- Battery conditioning: Set the temperature and let thermal estabilization, discharge the battery at C/3 until fully discharged and charge battery pack at 1C until 100% SoC and let battery pack relax.
- Set the desired operating point i.e 350kW discharge at -18°C.
- Discharge in steps of 10% OCV.
- Let the battery relax 4h in temperatures below 10°C and 30 min above 10°C in each step [8].
- Now proceed with the dicharge OCV curve in steps of 10% OCV.
- Repeat the process for all the operating points in terms of power and temperature along all the OCV.

2.3 Capacity testing

In this section, the main objective is to analyze the real capacity of battery pack under different operating points. The purpose is to test the battery pack under different working conditions. As other characteristics, the capacity higly depends external temperatures and external demands. For this reason, the testing under wide operating temperature range will be proposed. Despite the fact that this test would take more time than the coulomb counting method, the discharge test can give a better approach towards the real behavior of the battery. Also, this characterization process want to introduce the capacity testing under different load conditions. However, this capacity testing will only cover static and continuos working conditions. The purpose of this test is to exclusively know the amount of energy the battery could deliver under certain working points. This continuous discharge test could be use to define the initial energy amount of battery pack. Then, this information will be send to the BMS in order to know the battery initial SoC. Also, the BMS can calculate the remaining energy dependent on the temperature. Even different techniques could be used to discharge the battery pack, this work propose to do with constant current method. This proposal makes sense since the vehicle torque and accelaration are directly dependant of the current consumption. In Fig.2-11 can be seen a single cell discharging at different rates. This behavior could be similar to the one of the whole package, but adding the magnitude complexity and cell dispersion.

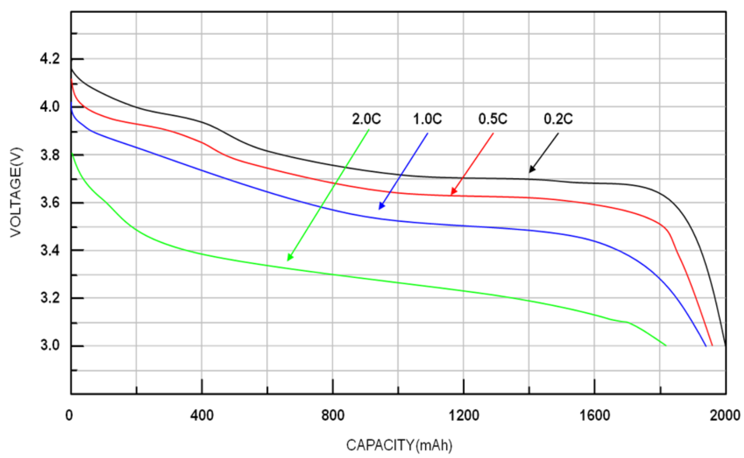


Figure 2-10: Example of discharge at different currents of single cell courtesy of Richtek Technology Corporation [31]

The procedure will consist on doing several discharges at low power rate due to the vehicle small electronics power consumption, plus several tests at high power conditions due to the traction system. In this case, the low power consumption test will be at 0.5kW, 1kW, 1.5kW and 2kW, aproximately 0.02C, if the nominalvoltage is 375V. In the low power case, the tests will be repated only at certain temperature points, -10°C, 0°C, 10°C, 25°C, 45°C. In high power, a greater number of operating points are interesting as the battery works close to its limit. The continous power discharge will be 0.2C(∼ 20kW, motorway consumption), 1.1C(∼100kW), 1.7C(∼ 150kW), 2.2C(∼ 200kW), 3.4C(∼ 300kW), with some resting in the last one. All of these calculations of C rates have been performed with nominal voltage of 375V, but the C-rates can change since the battery will work under certain voltage range. This test will provide information about the amount of energy displayed at different rates and therefore aid the BMS to make remaining battery estimations with power and temperature variables.

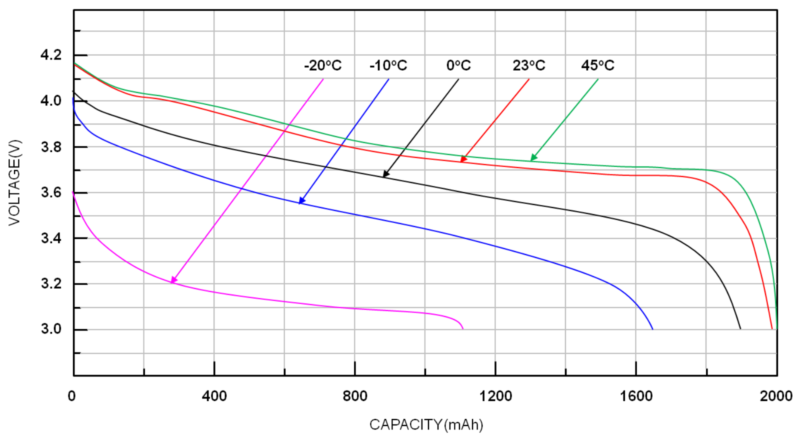


Figure 2-11: Example of discharge at different temperatures of single cell courtesy of Richtek Technology Corporation [31]

- Battery preconditioning: Charge battery pack a 1C until 100% SoC at 25°C and let battery pack relax for 3h. Execute only once before testing.

- Battery conditioning: Set the temperature and let thermal estabilization. Discharge the battery at C/3 until fully discharged. Charge battery pack at 1C until 100% SoC and let battery pack relax.

- Start the discharging process with 0.5kW of constant power at -10°C.

- Charge the battery and let it rest. The battery shall relax for 4h in temperatures below 10°C and for 30 min above 10°C.

- Repeat the process until all the low power operating point are covered.

- Start the process of high power curves, start with 0.2C and -18°C.
- Charge the battery and let it rest, the battery shall relax 4h in temperatures below 10°C and 30 min above 10°C.
- Repeat the process with different power ranges and in a temperature range from -18°C to 60°C in steps of 10°C.

Futher investigation could be done about the discharge testing in terms of power and energy, or power and capacity. This could be interesting to know the behavior under constant load conditions, such as motorway vehicle behavior. Additionally, this could introduce an easier interpretation to the mass public.

2.4 Charging testing

People, when buying an electric car, want a car with the same behaviour as an ICE vehicle. But, in electric vehicles, the energy refill is an important issue due to the speed of charging. With this testing, a better knowledge of the battery charging process is to be obtained. Understanding the behavior of the battery when charging could improve the charging techniques to obtain the perfect balance between charging speed and battery life.

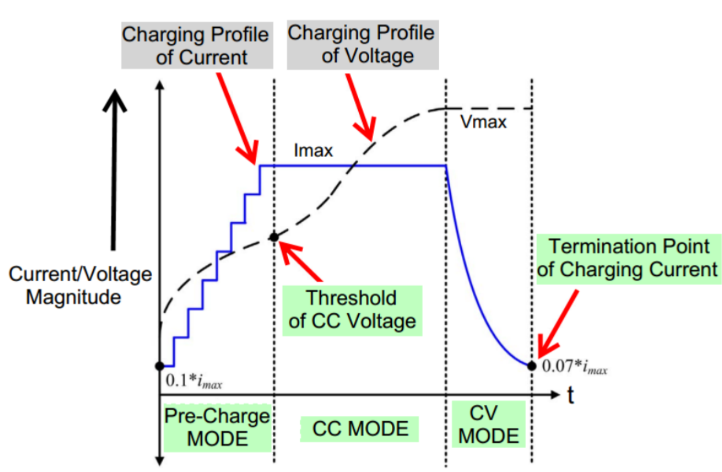


Figure 2-12: Typical fast charging profile [27]

Also, this information could be useful to know the energy aceptance of the battery in order to implement and improve energy recovery systems. The procedure could be quite similar to the discharging testing, and this test could be done in the same sequence. The difference will be the ratings because, usually, batteries have more power capability when they are discharged.

Since different power capabilities exist for charging process, several operating point will be defined. The C-rates operating points will be the same used in OCV section. The charging points will to simulate be normal charging modes, 3.7kW, 7.2kW. Fast charging mode with power rates of 22kW, 50kW and ultra fast charging mode with 150kW, and in nearly future, 200kW. Although this operating point is defined by power rating, charging will be done in a constant-current constant-voltage mode. As can be seen in Fig.2-13, the power tries to indicate the maximum reachable power, but the charging is done in CC-CV method. As always, this power operating will be combined with different temperatures in order to check the performance in all working temperature ranges, from -18°C to 60°C.

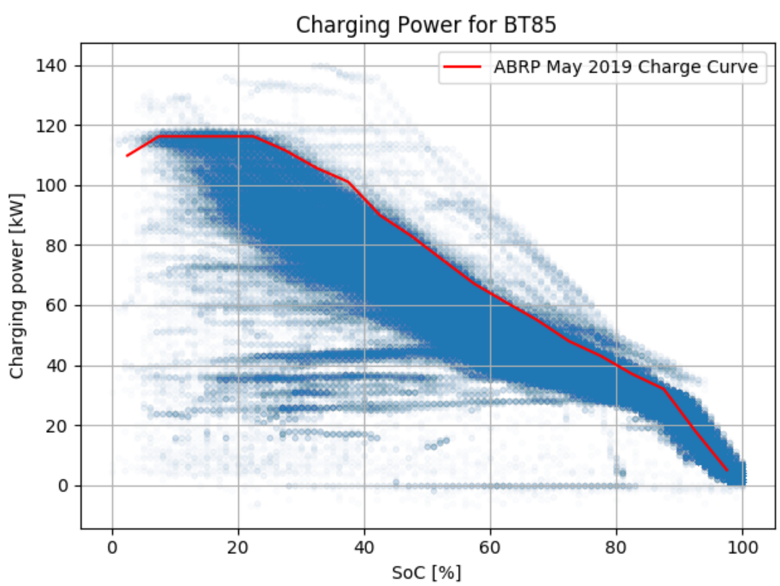


Figure 2-13: Example charging rates of Tesla model S 85D extracted from Tesla user forum: https://forum.abetterrouteplanner.com/blogs/entry/30-tesla-supercharging-summer-2019-update/

- Battery preconditioning: Charge battery pack a 1C until 100% SoC at 25°C and let battery pack relax for 3h. Execute only once before testing.

- Battery conditioning: Set the temperature and let thermal estabilization. Discharge the battery at C/3 until fully discharge, charge battery pack at 1C until 100% SoC and let battery pack relax.

- Start charging the battery at the operating points, start with 3.7kW (∼0.05C) and -18°C in constant current mode.

- Charge the battery and let it rest. The battery shall relax for 4h in temperatures below 10°C and 30 min above 10°C.

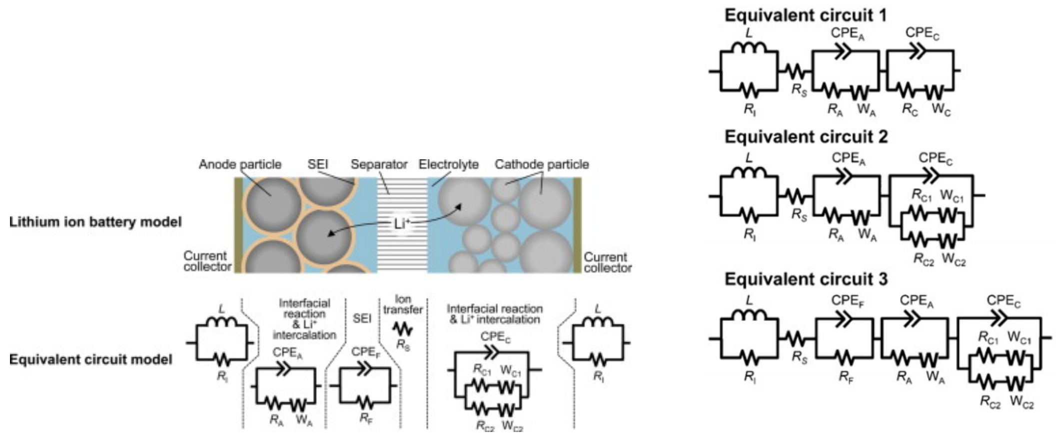
- Repeat the process with different starting power but charge in constant current constant voltage mode and in a temperature range from -18°C to 60°C in steps of 10°C.

2.5 EIS Characterization

Electrochemical impedance spectroscopy is an interesant test in the automotive sector to perceive the internal impedance of the battery. Choi et al. in [15] introduces a method to perform this test in HV battery packs. The impedance measurement determines the different resistance along a wide frequency range. EIS is very useful to determine the battery aging and its performance at different temperatures and , because the impedance has a direct relationship with the power delivery and battery losses.

With EIS, an accurate electrical model of the battery impedance could be extracted. As the behaviour, that can be seen in Fig. 2-14 consists on a several sets of impedance that act in different frequency ranges [52]. Moreover, EIS test could be a beneficial diagnosis tool for SoH indicator [20] of the battery [26].

This test will be performed accompanied by some relaxation periods in order to stabilize the battery chemical reactions. Since the test will be done regarding automotive requirements, the battery will be tested at several temperature operating points and



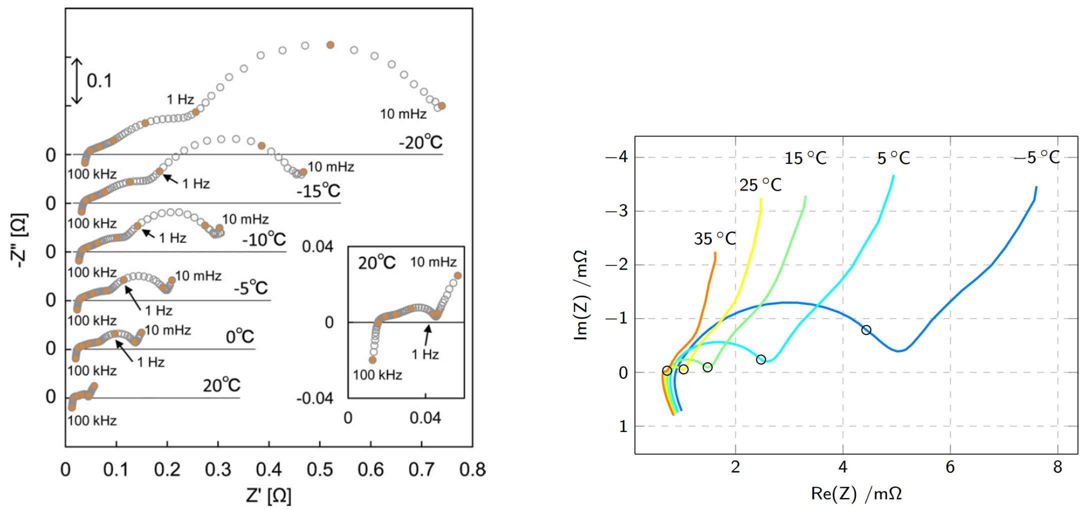
(a) Physical causes of battery impedance (b) Examples of EC models

Figure 2-14: Pyshical effect and equivalent circuit models

different SoC [19]. This project wants to propose a set of test that go from -18°C to 60°C in steps of 10°C. These various temperature testing points are defined due to the high dependency of the EIS on temperature changes [79],[72], [18], as can be seen on the graphics in figure 2-15. Note that in image b, the circles represent 1Hz frequency. Also, the several SoC operating points are due to EIS depence of SoC [65], [82]. The results can be observed in 2-16.

The test will be done every 10% of SoC in potentiostatic mode with 2mV RMS. This test will be time-consuming, but as more operating points the test has, better knowledge about the behavior of the battery will be obtained. The procedure of the test will be as follows:

- Battery preconditioning: Charge battery pack a 1C until 100% SoC at 25°C and let battery pack relax for 3h. Execute only once before testing.
- Battery conditioning: Set the temperature and let thermal estabilization, discharge the battery at C/3 until fully discharge. Charge battery pack at 1C until 100% SoC and let battery pack relax.
- When temperature is below 10°C discharge 10% of SoC at 1C and let relax for 4h.
- When temperature is between 10°C and 60°C discharge 10% of SoC at 1C and



(a) EIS at different temperatures from [49] (b) EIS at different temperatures from [66]

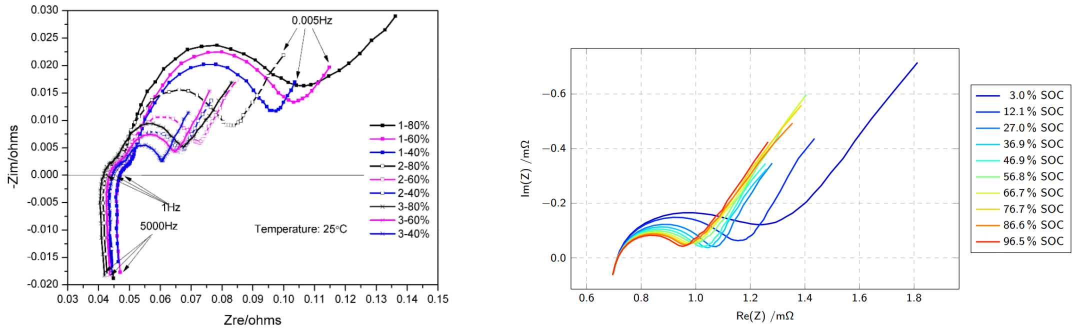
Figure 2-15: EIS temperature dependance from different studies

let relax for 30 minutes. Note that in EIS characterization the temperature play important role [8].

- Perform EIS test at desired SoC and temperature from 500 mHz and 10 kHz with 10 frequency points per decade.

- Repeat the process for all the temperature and SoC combinations.

In this case, the purpose is to do an exhaustive test of the battery pack under differente conditions. Note that two different relaxations periods are selected in accordance to the behaviour described by Barai. A in [8]. This effect is caused by the ionic re-distribution and solid state diffusion at low temperatures. The first loop of the test will be done at room temperature, 25°C, in order to know normal rating operation. The following loops will start at -18°C and finish at 60°C. Due to the high time consuming of this test, the number of operating points could be reduced to obtain result faster, especially in low temperatures, but the quality will be reduced.



(a) EIS at different SoC from [82] (b) EIS at different SoC from [65]

Figure 2-16: EIS SoC dependance from different studies

2.6 HPPC

Hybrid pulse characterization is used to undesrstand the behavior of the battery pack in dynamic conditions. This test will cover the charge and discharge under different pulse sizes. With this test, the instantaneous power capability and the dynamic internal resistance can be obtained. These dynamic tests are highly important for automotive companies because they need to know the dynamic characteristics in order to understand the behavior -of the car battery in the road with acceleration and regenerative braking. Some researchers have studied HPPC and have done several tests on real behavior to single cells [70]. Other international organizations make some recommendations for this characterization [16]. Even several HHPC profile tests have been developed. The most common profiles among researchers is the IEC standard. But since this work wants to propose several and exahustive testing driven by automotive requirements, the testing will be redefined with more operating points in terms of SoC and temperature. With these power operating points, the charge power of regenerative braking is also covered.

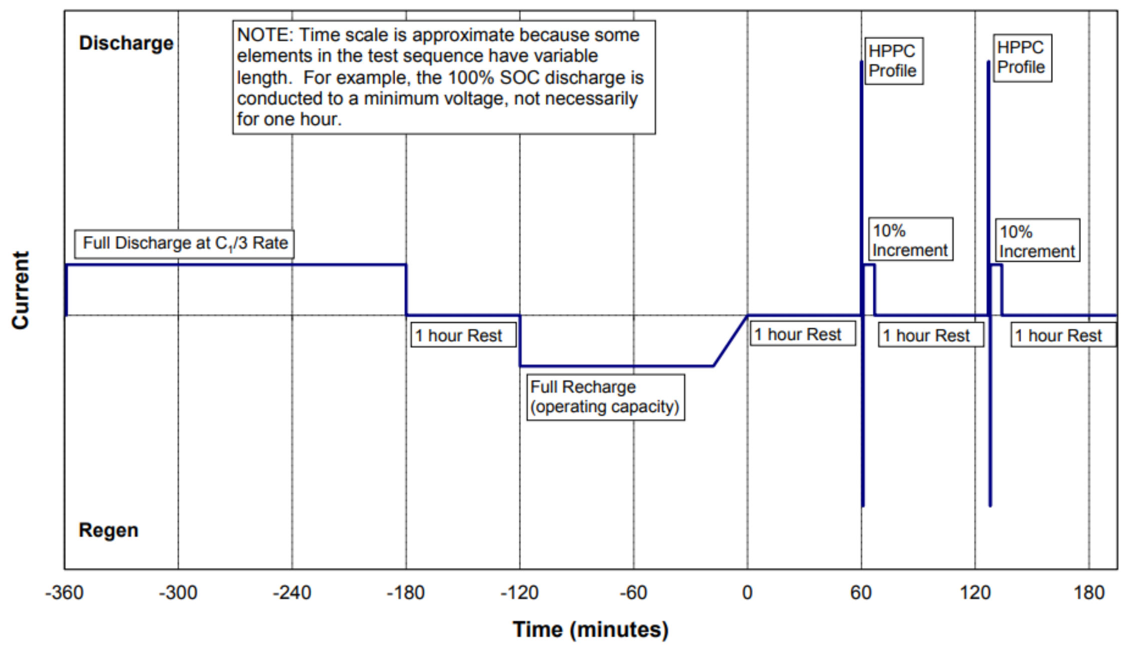


Figure 2-17: HPPC general picture profile

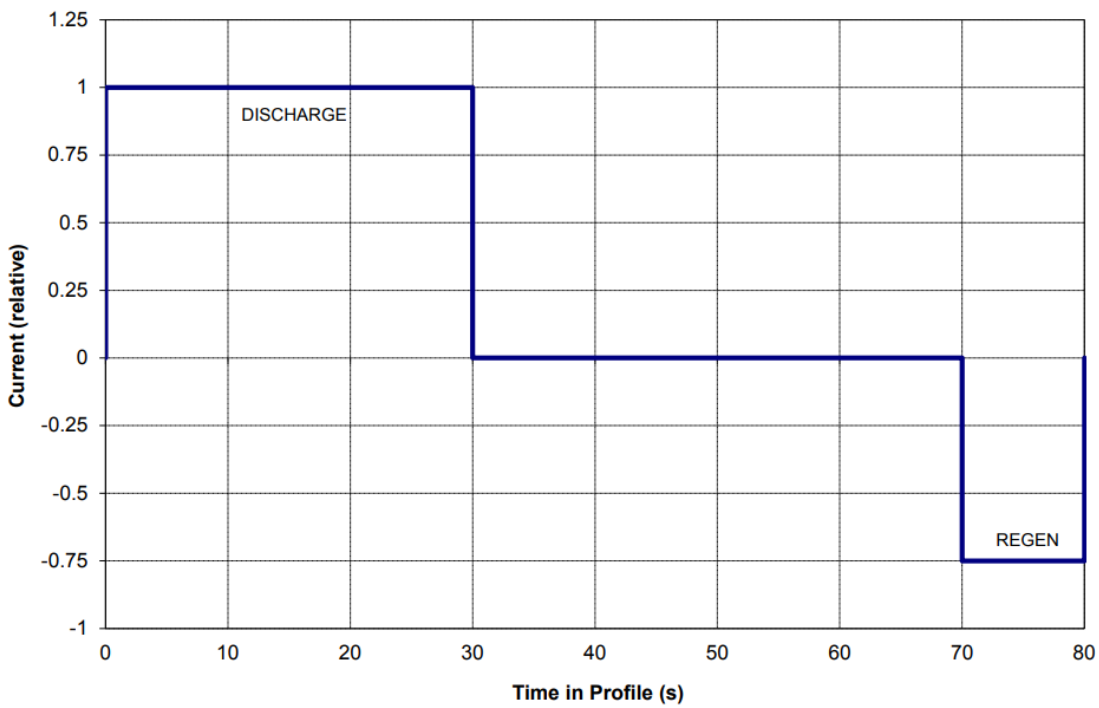


Figure 2-18: HPPC zoom of profile current pulse

Because the present technology can reach up to 60kW [78], [77], [29] of regenerative power, even the power generated from kinetic energy of a vehicle at 120km/h to

0km/h is bigger. This project wants to introduce the HPPC of Jon P. Christopherson in [16] but with some variations and adding more interesting operation points from the automotive sector perspective. To improve this test for automotive purpose, tests have to be done between -18°C and 60°C in steps of 10°C at C rates of, C/2, C, 2C, 4C and 5C along all of SoC operating ranges, from 100% to 10% in steps of 10% SoC. In this test, between each SoC operating point, the battery will be discharged at C/5 until the next SoC point.
In Fig.2-17 a general picture of HPPC profile can be seen, with the preconditioning and two pulses. In Fig.2-18 the zoom of single pulse power profile can be observed too. In the general, picture a preconditioning can be seen from -360 minutes to 0 and just before the start a 1 hour resting period. After this preconditioning, the test will start with the desired C-rate. Note that the time scale is relative and orientative and should be adapted to the project characterization and the current is represented in relative scale. In this case 1 means the desired C-rate for the test.

- Battery preconditioning: Charge battery pack a 1C until 100% SoC at 25°C and let battery pack relax for 3h. Execute only once before testing.

- Battery conditioning: Set the temperature and let thermal estabilization. Discharge the battery at C/3 until fully discharged. Charge battery pack at 1C until 100% SoC and let battery pack relax.

- Execute the HPPC defined profile at desired C-rate and discharge at C/3 until the next SoC step. The SoC point goes from 100% to 10% in steps of 10%.

- Perform this test for each C-rate and temperature defined.

Note that in all the test sequences, the relaxation period and the thermal stabilization will be of 30 minutes for temperatures above or equal to 10°C and of 4h in temperatures below 10°C.

2.7 Real environment driving cycles

Under the point of view of automotive manufacturers, these testing procedures could be the most interesting ones. This work wants to propose several tests of the battery pack under different dynamic and nearly real behaviors. This test could provide important information to automotive companies, such as the car ranges or the behavior in real conditions, with accelerations and brakings. A lot of regulations exist in different countries around the world, and manufacturers shall adapt themselves to these regulations. Since the regulations are different, several driving cycles exist. The purpose of this project is to define a test sequence for the battery pack under different driving cycles. In this work, the testing sequence and the driving cycles will be proposed. To test these cycles in a battery pack, the cycles shall be translated to current or power battery consumption. This consumption highly depends on the type of car, the drag force, the road slope and the inertial force as can be seen in, [55], [80], [83]. The conditions can be simulated in the HiL and several cases would be tested. In this section, the most popular driving cycles will be proposed, but more driving cycles exist and other technical papers want to develop better profiles like Zhao et al. in [88]

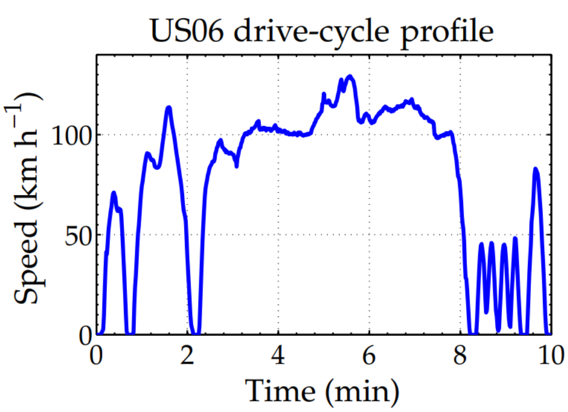
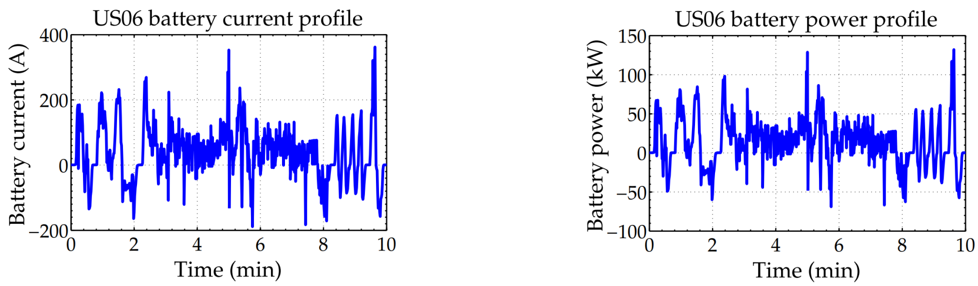


Figure 2-19: US06 profile cycle

All of the driving cycles that will be explained should be executed following the next steps:

- Battery preconditioning: Charge battery pack a 1C until 100% SoC at 25°C



(a) US06 Current profile

(b) US06 Power profile

Figure 2-20: Example of current and power profiles calculated from real driving cycle [55]

Table 2.3: Main characteristic of driving cycle test

Cycle	Duration (s)	Distance (m)	Maximum speed (km/h)	Average speed (km/h)	Maximum accel. (m/s2)	Idling time (%)	Road coverage
NEDC	1180	11000	120	33.6	1.04	23.7	Urban-motorway
WLTP	1800	23266	131.3	46.5	1.67	12.6	
ARTEMIS	3143	51687.4	150.40	59.20	2.861	9.64	Urban-Road-Motorway
FTP-75	1877	17769	91.2	34.1	1.48	18.0	
JC08	1204	8159	81.6	24.4	1.69	28.7	Urban-motorway

and let battery pack relax for 3h. Execute only once before testing.

- Battery conditioning: Set the desired temperature in a climatic chamber. Dicharge/charge the battery pack at C/3 until 100% SoC at the desired temperature and let battery pack relax for 3h.

- Start to discharge the battery following the driving cycle at -18°C from fully charged to fully discharged.

- Increase the temperature of the test in 10°C.

- Post-conditions: Charge battery pack in CC-CV until 100% SoC at the next temperature step. Remind that if the temperature is below 10°C the relaxation time should be of 4h and 30 minutes in other cases.

- Repeat the process until all the operating point will be covered.

NECD

This cycle was used to homologate the vehicles until the Euro6 European regulation. This cycle consists on repeating an urban ECE cycle 4 times and adding 1 cycle of motorway behavior [11], [67], [63]. In Fig.2-21 the whole NEDC cycle can be observed. As has been explained, from the start to second 780 the ECE cycle is repetead 4 times. After that and from second 780 point to the end, the motorway cycle will finish the whole driving cycle. This cycle has been criticized for being too far from real behaviour as it has slow acceleration profiles and long idles or contant speed periods. Despite these opinions, automotive manufacturers could benefit from the analysis of this cycle in order to cover the homologations.

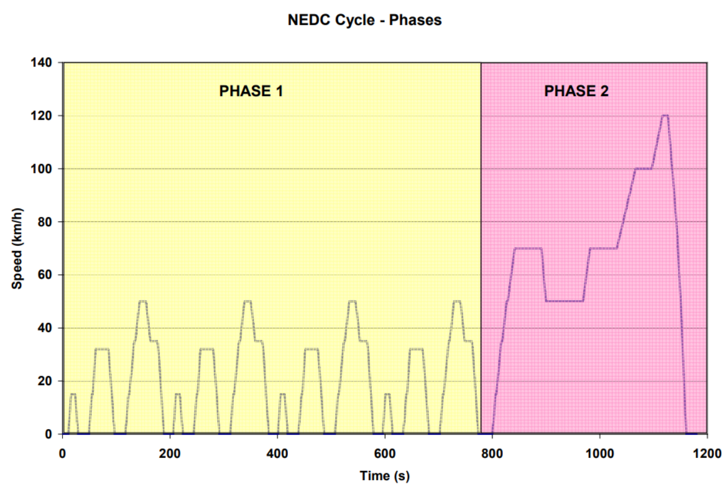


Figure 2-21: NECD profile cycle

The proposal of the project is to cover this driving cycle but under different conditions, different SoC and different temperatures. In this case, the temperature could play an important role since the performance and the range is strongly affected by the temperature. The proposal consists on doing the test repeating the sequence from 100% of SoC until 0% of SoC from -18°C to 60°C in steps of 10°C. Note that since the cycle is in defined in speed mode, it shall be converted to current profile for the battery.

WLTP

Nowadays, Europe is working on a more realistic driving cycle. The regulation committes want to use the WLTP (Worldwide Harmonized Light vehicles Test Procedure) and its WLTC (Worldwide Harmonized Light vehicles Test Cycle) for homologation purposes. WLTP has 3 different classes of test. The most interesting class is the conventional family car, the class 3. This test cover different driving escenarios such as urban driving, suburban driving, extra-urban driving, and a highway zone.

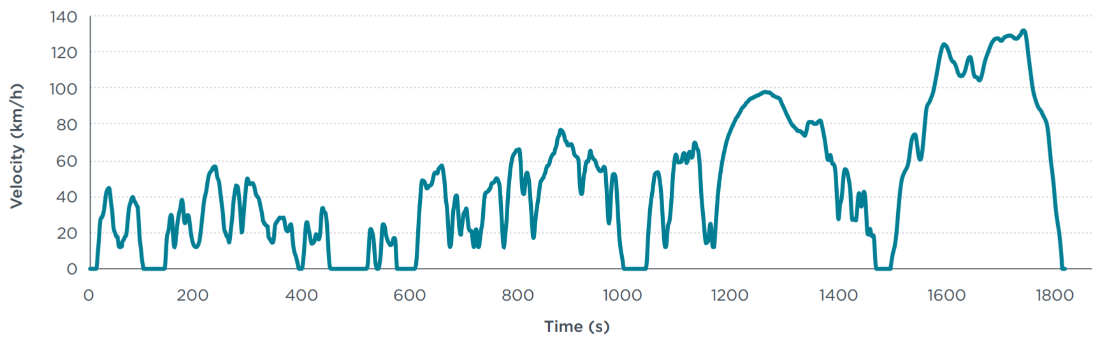


Figure 2-22: WLTC profile cycle

As in NEDC, the testing proposal procedure will be similar. Repeat the sequence from full chrage to fully discharged at different temperatures.

ARTEMIS

This driving cycle has different modes and has a better approach to the real world [24], This cycle is widely used by researchers due to its closeness to a real environment driving range, [1], [38], and pollution, [5], [6] of ICE vehicles.

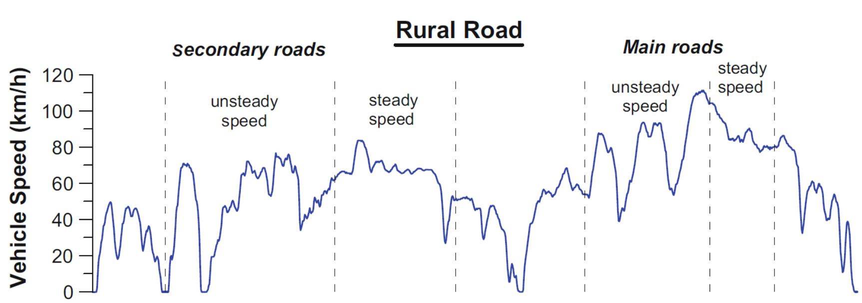


Figure 2-23: ARTEMIS rural profile cycle

ARTEMIS has three different cycles: rural, urban and motorway. Usually, these three cycles are executed together in one big cycle to reproduce all the cases in one test.

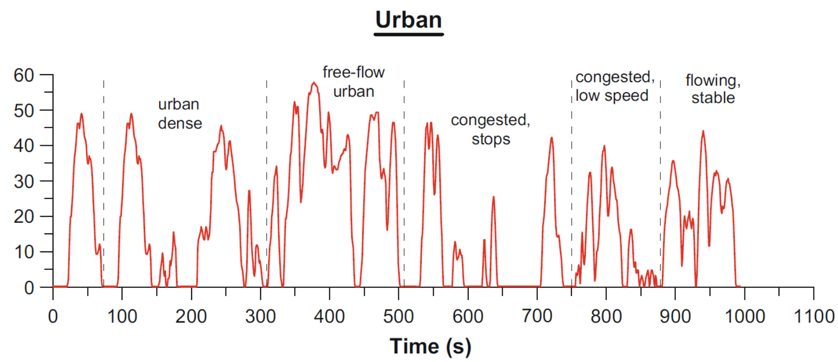


Figure 2-24: ARTEMIS urban profile cycle

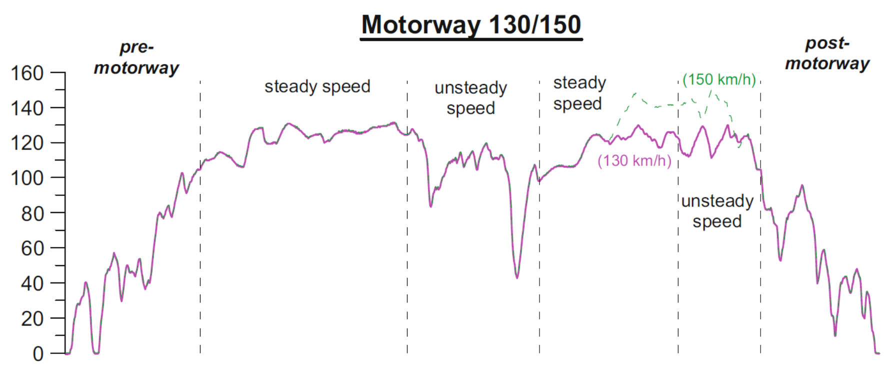


Figure 2-25: ARTEMIS motorway profile cycle

The proposed test procedure will be the same as before, repeat the whole cycle from 100% of SoC to 0% of SoC at different temperatures in the battery pack temperature working range. The full ARTEMIS cycle looks like Fig.2-26.

- Battery conditioning: Charge battery pack a 1C until 100% SoC at 25°C and let battery pack relax for 3h.

- Set the temperature to -18°C and have a the relaxation period. Start to discharge the battery following the driving cycle from fully charged to fully discharged.

- Charge the battery pack in CC-CV until 100% SoC at the next temperature

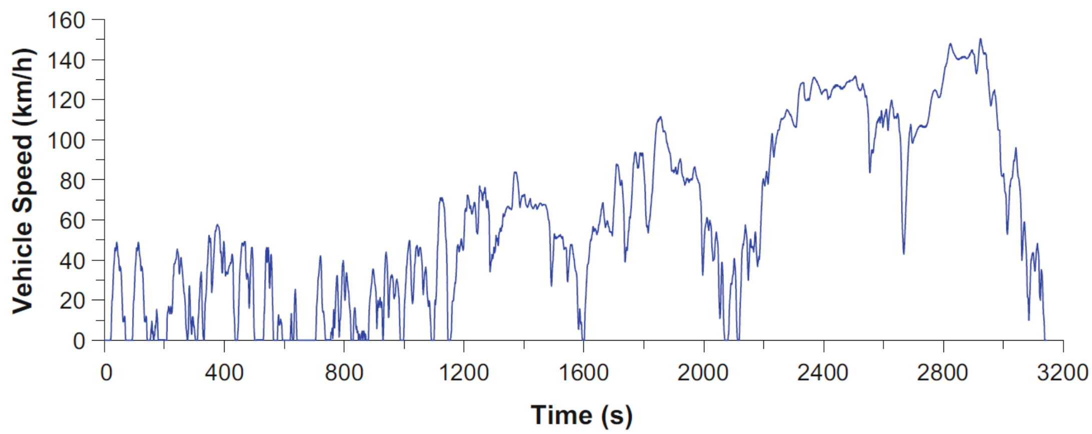


Figure 2-26: ARTEMIS full profile cycle

step. Remember that if the temperature is below 10°C the relaxation period should be of 3 hours, or 30 minutes in other cases.

- Increase the temperature of the test 10°C and repeat until the temperature range is covered.

FTP-75

This driving cycle is the official one in the USA and was developed by the EPA in 1975 to measure the emissions of passenger cars and ligth-duty trucks. This cycle represents some commuting, urban and highway driving behavior, [34], [24]. Actually, This FTP-75 is an extension of FTP-72, developed three years before but adding a cold star phase at the beginning.
The proposed test procedure consists on executing the cycle several times until fully dicharged, then charge the battery to full charge state and repeat with differente temperatures. Thanks to this test, the battery can be characterized for different climates in the USA. Although more driving cycles with different profiles exist in USA, the most widely used is the FTP-75 due to its characteristics. Another test that could be interesting is the Highway Fuel Economy Test cycle (HWFET) because it covers the highway behaviour, the real challenge of the electric vehicle.

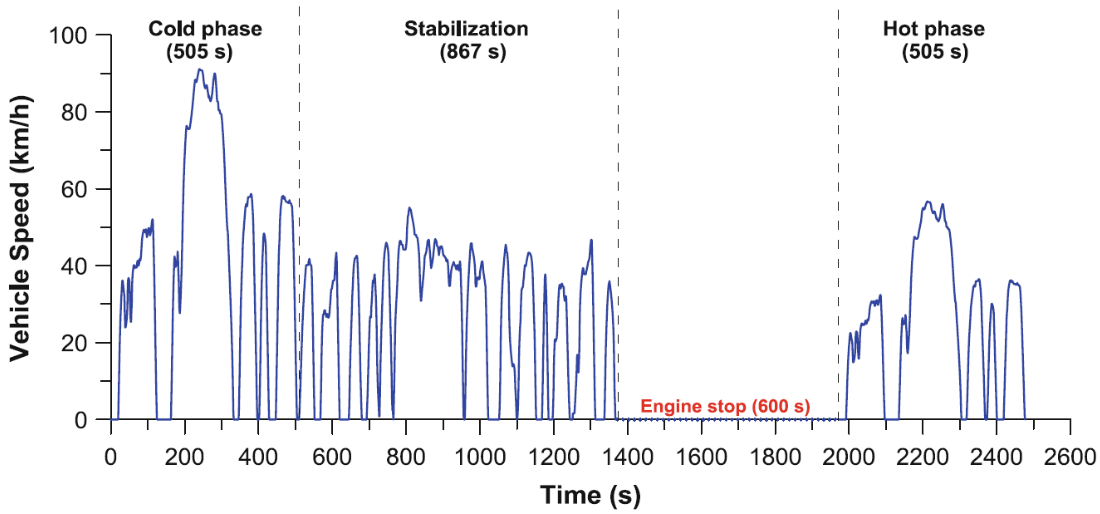


Figure 2-27: FTP75 full profile cycle

JC08

Another widely used cycle is the JC08, the official Japanese cycle, to measure emissions. Since 2011 this is the only valid cycle in Japan, at least for domestic vehicles [33]. This cycling wants to cover an urban-motorway behavior in the surroundings of Tokio with big idle times and some high speed times. Technical information about this cycle can be found in the appendix.

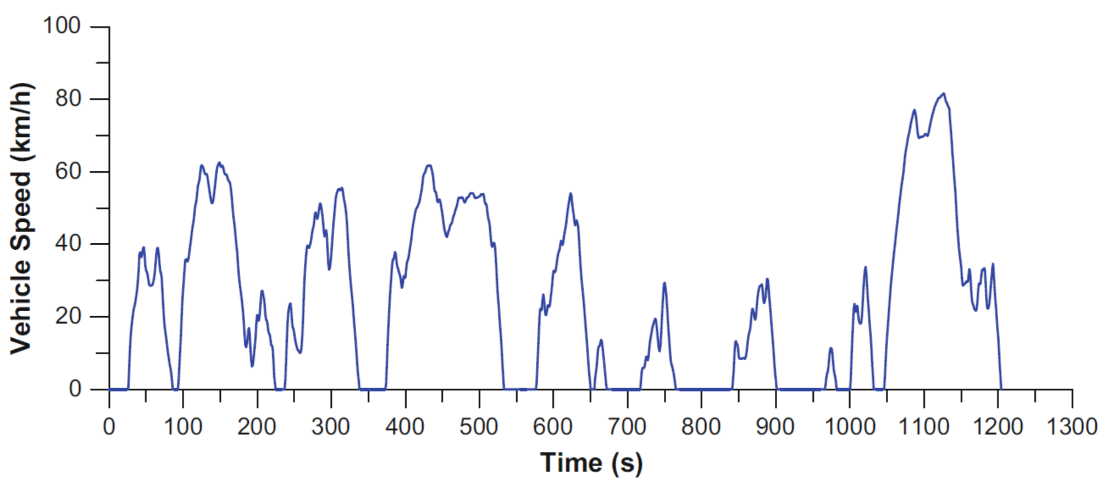


Figure 2-28: JC08 full profile cycle

Chapter 3

Characterization set-up construction

In this chapter, the construction of the laboratory set-up to perform the tensting on the battery pack will be explained. The scope of the chapter will cover from the AC energy source to the energy return to the grid. Tesla Model S P100D battery pack will be used to have a reference of the battery pack size, but the scope is to design a test bench to cover a wide range of battery packs in the market. The main idea is to create a test bench that can allow testing the battery pack system under different operating ranges and temperatures. To do that, the test bench must have a climatic chamber, a controller power supply to charge the battery pack and an electronic load to simulate the discharging behavior. The Test bench also needs communication and data storage systems in order to control the system and to store important information for later analisys.

3.1 Technical assesment

Firts of all, the power requirements of the system must be fulfilled. The battery pack needs at least one energy source able to reach 150kW to simulate the fast charging process. Moreover, it would be convenient to design a energy source of 200kW for further challenges since future developments are working at this power. [61]. The voltage capability should be up to 1000V and the installation must also ensure a current capabality of 350A to cover all the possibilities. Furthermore, to dicharge the battery within its maximum rates, an electronic load of 500kW should be used, as even the motor can develop more power. The peak power of both motors performance of Tesla Model S P100D working together can reach nearly 600kW. The present battery technology can only deliver 451kW. These two points are the main problems in this set-up because the high peak power that the battery can demand. Other variables such as temperature, voltage operating ranges or control of the testing process, would be easy to implement.

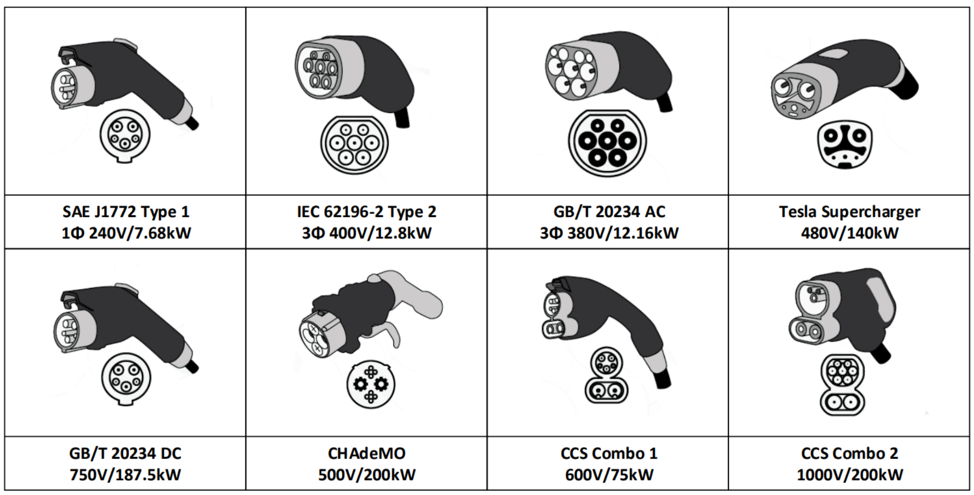


Figure 3-1: Battery charger connectors [61]

The installation must withstand power peaks up to 200kW and to charge the battery. The load should work up to 500kW and should be programmable to change the power demand profile. A temperature chamber is needed to control the enviroment conditions. Also, control and data adquisition equipment is needed. To test the impedance spectroscopy an EIS tester is required as well.

3.2 HiL

A hardware in the loop system (HiL) is a type of technique used to develop complex systems. The HiL allows the user to test a DUT simulation in different conditions and in real time [43]. Usually, these types of set-up are composed by a device to test, in this case the battery pack, hardware equipment to simulate the desired condition, the battery cycler, different measurement equipment, such as power analyzer, EIS generator and an impadance analyzer and oscilloscope. Eventually, a PC and a control system to load the simulation scenarios, to collect and analyze the data and to control the safety in the laboratory would be introduced as well. This composition will help to simulate the desired conditions for the testing. With this arrangement, the defined testing procedures can be loaded into the battery cycler and the climatic chamber to create appropiate conditions for testing. Also, this system can communicate with the BMS to know all the internal state of the battery and to check how the battery will behave once it is implemented in the vehicle. This set-up will also have a ethernet communication system in order to control all the equipment remotely. The contribution of this type of development is its flexibility, its size and its development speed. With this configuration, several battery packs can be tested. Rapid deployment of mathematical models can be done. Since the test can be performed automatically, the rapidity of the characterization can be enhanced under different working conditions.

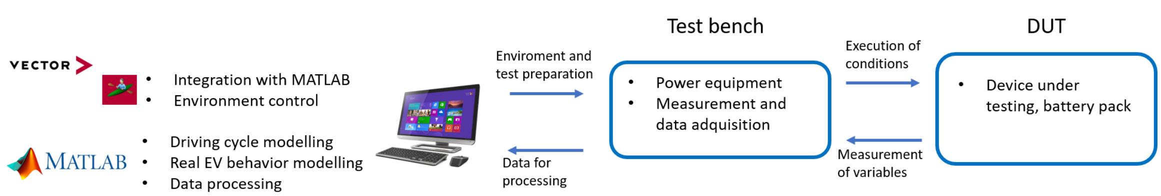


Figure 3-2: Test setup concept

3.2.1 Arquitecture

To implement this test bench and to create an automatized environment, a HiL will be proposed. In Fig.3-3 the general arquitecture of the whole system is explained. The main idea is to control all environment conditions, the mathematical models of driving cycles, the thermal conditions, and current charge/discharge profiles from a host PC. Additionally, the test execution, the data acquisition and the data process must be controlled from the same PC as well.

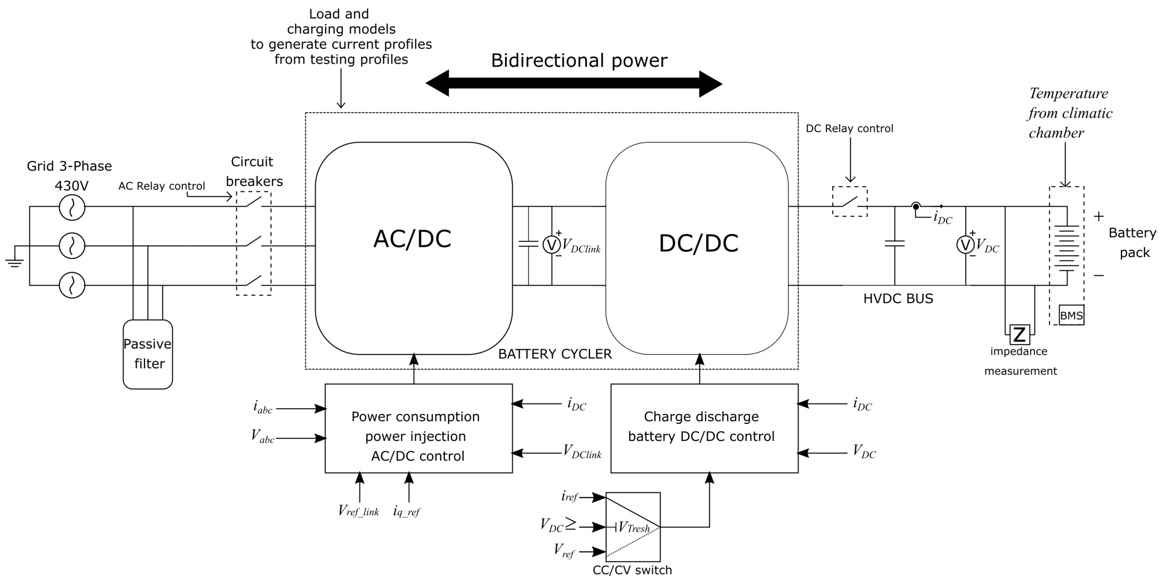


Figure 3-3: Scheme of power circuit

The disposition will consist on different laboratory equipment connected in an internal ethernet subred connected to a ethernet switch. This communication configuration provides easy data acquisition from the equipment and easy control of the all devices from the PC. This control of devices will provide high level of automatization testing process. In Fig. 3-4, the proposed ethernet network can be observed.

Another communication network will be set between the battery pack electronics, the BMS, and the VTsystem. This communication network will be via CAN. With this CAN network and with the help of VTsystem, the BMS can be controlled and it can provide information about the state and reads of each cell and module. With this CAN network, the objective is to have another information source and to check how the battery works in a deeper level.

The last network is the HV power network, composed by the HV power part of the system. It goes from the power supply of the battery cycler to the high power DC interconnection between battery cycler and the battery pack. The battery cycler will be connected to the electrical grid through three phase feeding and the battery will be connected to the battery cycler through a DC bus. Since voltage level above 50V is defined as high voltage in automotive industry, safety plays a very important role

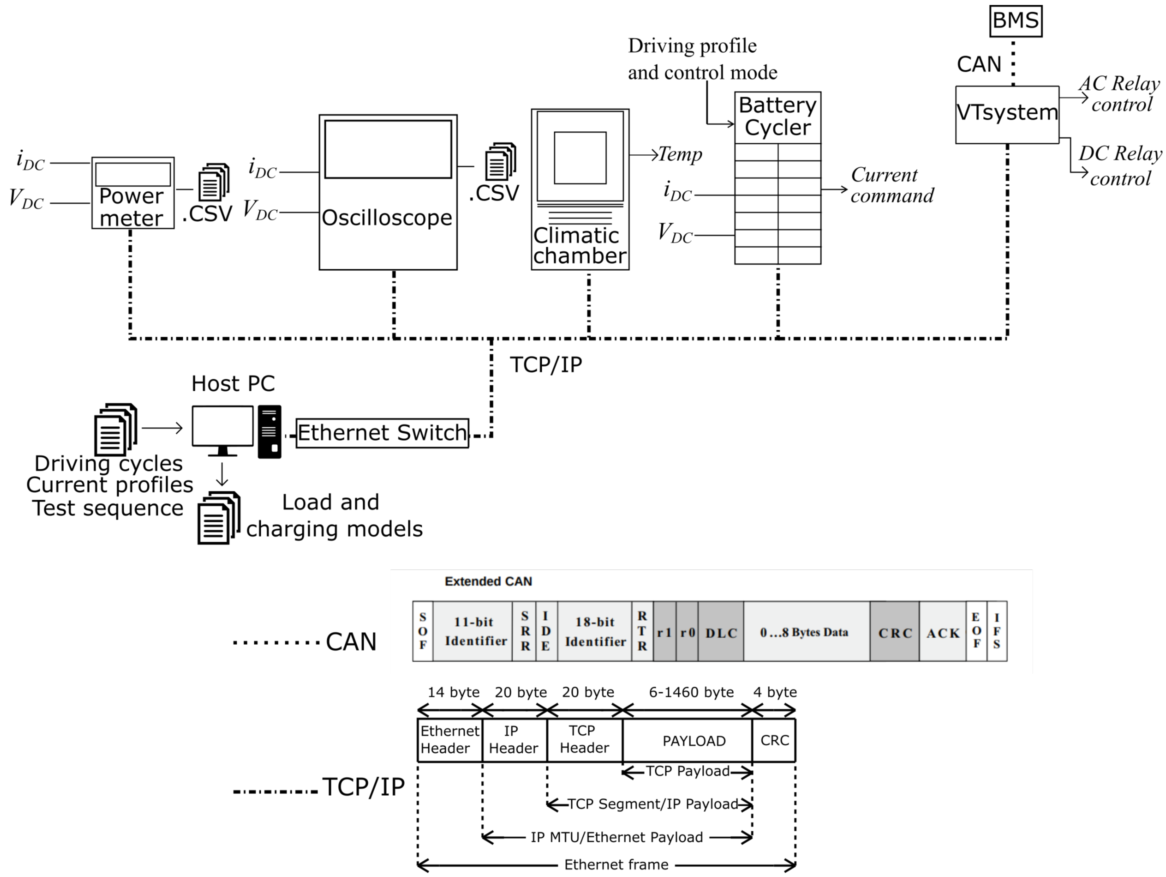


Figure 3-4: Communication networks and safety control commands

in this network.

Some notes shall be added to this configuration, the EIS cannot be remotely controlled and the control of VTsystem over electrical drives is a logical control with 12V commands for positive logical level.

3.2.2 Laboratory equipment

Battery cycler

Nowadays, due to the increase in electric vehicle production, several companies offer solutions for battery testing, from single cell form to the whole battery pack. Companies like ©CHROMA ATE INC, Arbin Instruments© or EA Elektro-Automatik GmbH & Co. provide solutions for battery testing. Actually, CHROMA and Arbin provide similar solutions, but Arbin is more especialized in battery purposes and offers easy integration with third party EIS measurement and climatic chambers. All the profiles needed and defined in the test sequence can be charged in this battery cycler. Also the battery cycler can communicate with other equipment and the PC through CAN or Ethernet to synchronize and automatize the testing procedure. Certainly, Arbin's Regenerative Battery Testing can provide the voltage, current and power desired levels. As additional information, this battery cycler can be easily integrated with a redundant safety monitoring system to avoid safety problems. These regenerative instrument types are economic and highly efficient when working as this kind of equipment can return the energy to the grid or to energy storage systems. In their webpage `https://www.arbin.com/products/battery-test-equipment/` Arbin Instruments provide futher information about the whole specs and possibilities of their instrumentations.

Figure 3-5: Arbin Intruments batter cycler

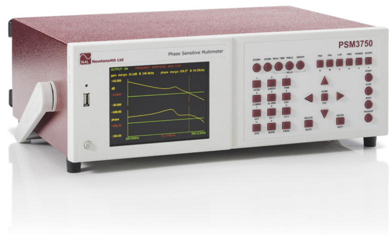
Climatic chamber

The climatic chamber should have a remote control to set temperatures and should operate between -18°C and 60°C. Although the automotive standards are higher, since the battery pack will be tested at battery pack system integration level without any cover, the testing range shall be between the modules operating range. The chamber used for this testing procedure will be the Weiss Technik © Test System for Lithium-ion Energy Storage Systems, due to the battery pack size and safety. Full specifications can be observed in the appendix.

Figure 3-6: Weiss technik climatic chamber

EIS

To perform the EIS testing, a high quality laboratory equipment is needed. In these test cases, every small detail is crucial, from the connection with the signal generator to the solder of the cells inside the battery pack. Most of the EIS measurement equipmentis thought to test single cells, but some companies provide solutions with power boosters to test modules or whole battery packs.



(a) PSM3750 Frequency Response Analyzer

(b) BATT470 Impedance Analyzer

Figure 3-7: EIS measurement equipment

Actually, this solution provided by © Newtons4th Ltd offers a solution for different test equipment, one function generator and the impedance analyzer. The same company also provides a software to work with the device and obtain the EIS measurement of the DUT. How this set-up works and how it should be configured can be seen in the appendix.

3.2.3 Data acquisition

Oscilloscope

To analyze the fast transients of real driving cycles and the HPPC and to validate stable levels of voltage and current during transients and in permanent regime, an oscilloscope will be needed. With the oscilloscope, the dynamic evolution of the current and voltages in the battery pack will be analyzed. In this case, a Teledyne Lecroy 4 channel oscilloscope will be used.

Figure 3-8: Teledyne Lecroy Wavesurfer 3014z

Power analyzer

This type of equipment allows to log all the data in terms of current, voltage and power. This equipment is highly interesting to obtain trustful measures of these values due to its high precision measurement. With the power meter data logged, the data can be extracted in CSV or other file formats and can be easily printed in a graphical way. An automatic data logging and information treatment can be implemented in order to improve the large amount of data generated with the testing.

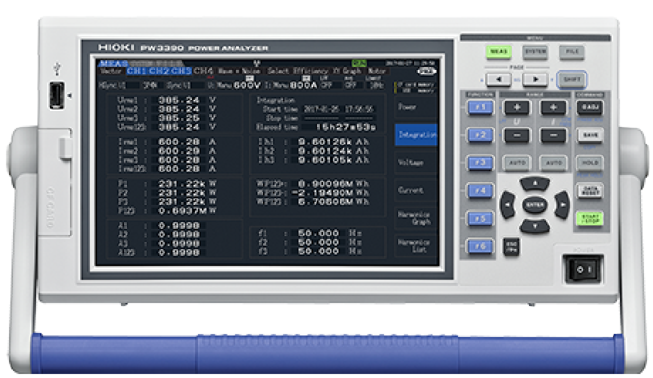


Figure 3-9: POWER METER PW3390 – © Hioki

3.3 Testing automatization

To improve the testing range and the number of tests executed, a test automation plan will be proposed. To do that, a testing environment is needed. Since the VTsystem is used, the automatization will be proposed with © Vector CANOE and © Vector vTEST, , commonly used programmes in the automotive industry.

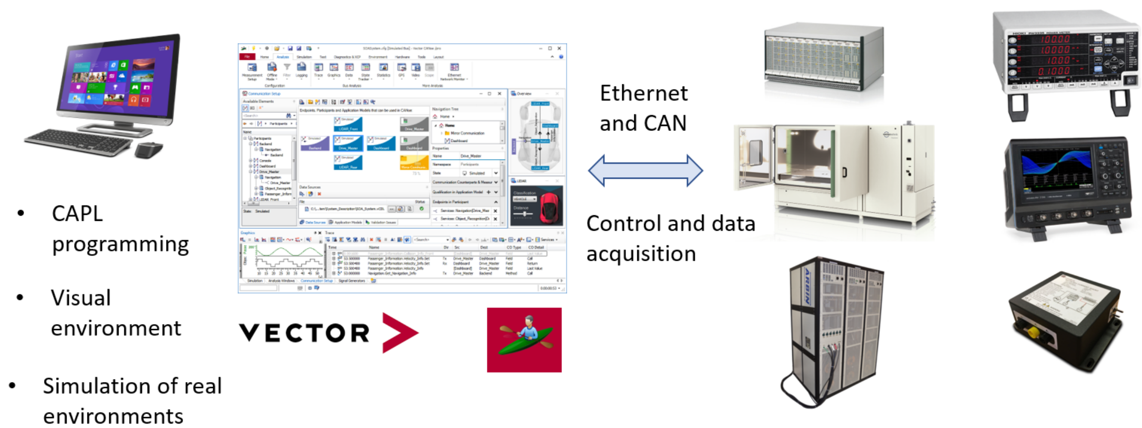


Figure 3-10: Configuration of simulation environment

In CANOE environment all the control-related and communication with the equipment will be done trough several layers of programming in CAPL. This enviroment will be used to simulate the vehicle in road conditions. To design and create the testcases and do the automatization, the Vector vTEST studio will be used. vTEST Studio lets the user to create and design different testcases and test sequences to control and execute them automatically.

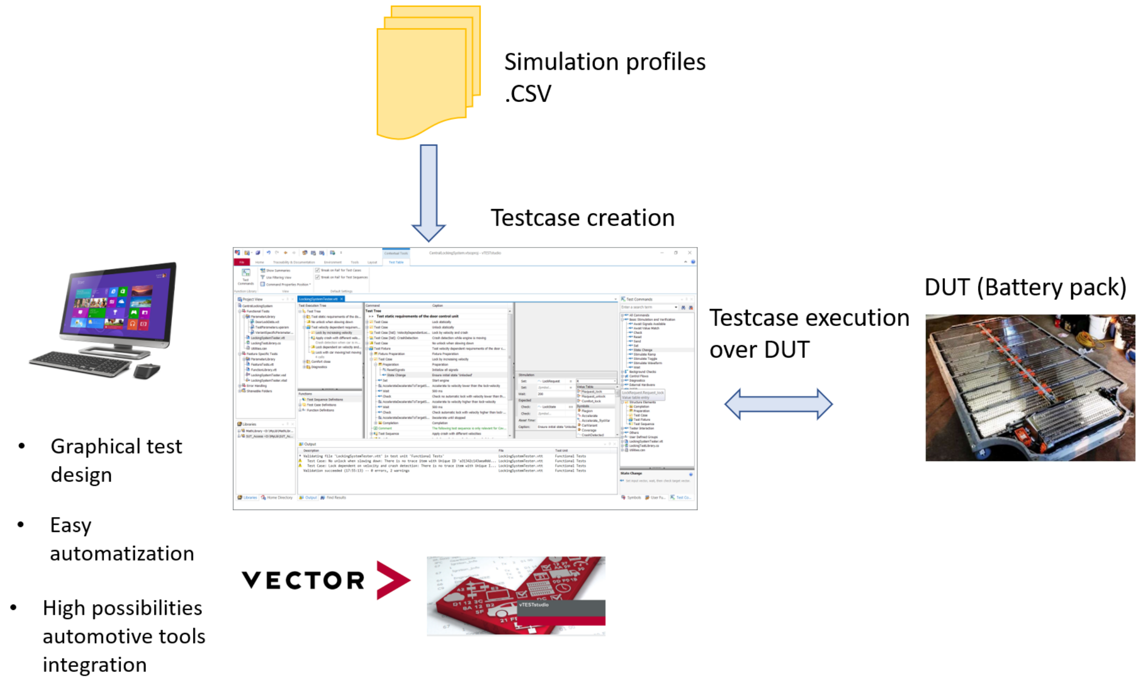


Figure 3-11: Automatization and testcase execution

Chapter 4

Conclusions

This chapter will present the final picture of the overall work. A summary of different testing process of different books and research papers can be found in this project. This could help battery researchers to have a guide for testing. The battery characterization process is highly important for the BMS to control and and obtain the utmost performance of the electic vehicle battery pack. The wide range testing of the work with different characterization techniques provides important information about the battery and its behavior under different conditions. With this testing procedure various ECM and other mathicmatical models could be defined to implement in the BMS.

With the testing procedure an inital condition in order to know the remaining capacity could be modeled.

The capacity testing provides the BMS with information about the remaining energy if the conditions are constant and continuous.

To control and to improve the charging times, the charging testing could be used. The information extracted with the charging testing could help to implement a better charging algorithm.

The EIS characterization test provides the tester with information about the SoH of the battery to check the battery aging status, as well as with important data regarding the battery pack impedance to analyze its performance.

To analyze the unquestionably high power demands and how the battery behaves in relation to large amounts of power demand, regenerative braking behavior and in cases of dynamic resistance to high power demands, the HPPC is proposed.

Finally, the most important test in terms of real driving range and the most visible one for the final user is the differen tests simulating real driving behaviors. With this test an estimation of the driving range can be calculated to give for the final user an average driving range.

With all of these tests executed, manufacturers can ensure the battery´s theoretical behavior and can also emphasize in the desired designing goals and put their developing efforts into improving the key and weak aspects of the battery pack for the electric vehicle.

4.1 Problems found during the research

The main researches about battery technologies characterization are focused on the battery cell behavior. Since the whole battery pack of an EV contains several cells, small differences in the chemistry and manufacturing problems may emerge. For this reason, a characterization of whole pack is crucial in order to be integrated in the final EV. Another problem found was the present defined testing procedures. Some internal regulatory institutions try to give advice about a basic battery testing, lacking the desired precision in this project. The final problem found was related to the laboratory set-up cosntruction. Various obstacles were faced when trying to find a valid laboratory equipment to test the present EV whole battery pack technologies.

4.2 Testing contribution to improvement

Since this work presents different testing methods explained, defined, and unified in one single project, it aims to help researchers to have an overall picture of how the testing should be done in order to accomplish the desired purpose. In this project, an exhaustive testing is proposed in order to analyze the battery pack behavior under a wide variety of working conditions, with different power demands, environmental conditions and dynamic conditions. This deep testing will provide a better approach towards the theoretical battery pack behavior in the real world, improving the product quality and performance.

4.3 Future directions

The future development of this work could go in several directions, from improving the testing quality adding different environmental conditions and variables to including different and new characterization techniques. Potential future advancements are listed hereafter:

- To validate the test sequence in laboratory environments and to check all the testing processes in a laboratory.
- To design the mathematics behind battery packs with the proposed testing procedure in order to implement all of these models in a BMS to improve the battery management. This can help to improve the fuel gauge, the power delivery and the driving range.
- To add more environmental variables to the test sequence that can affect the battery behavior, such as pressure or humidity in order to develop more realistic models.
- To develop an actual daily behavior of the electric vehicle and a more realistic testing cycle including periods of driving and periods of charging and to test the battery over a daily basis behavior.

Appendix A

Tehcnical datasheets

A.1 Panasonic NCR18650B Cell

Lithium Ion

Panasonic NCR18650B

Features & Benefits

- High energy density
- Long stable power and long run time
- Ideal for notebook PCs, boosters, portable devices, etc.

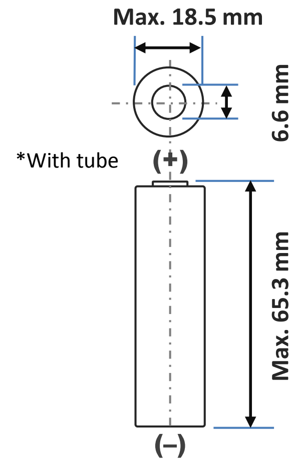
* At temperatures below 10°C, charge at a 0.25C rate.

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

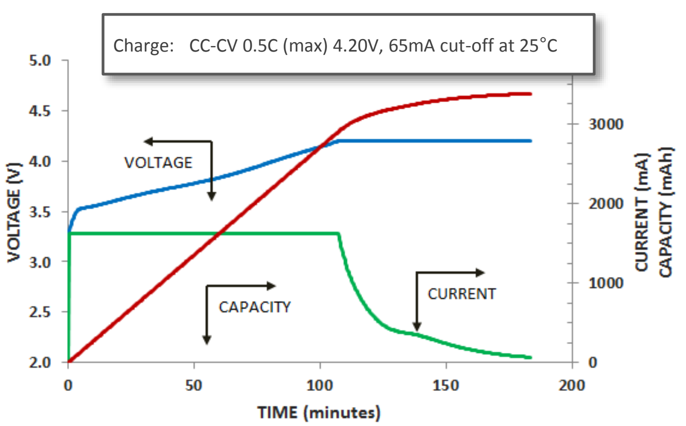
(1) At 20°C (2) At 25°C (3) Energy density based on bare cell dimensions

Dimensions

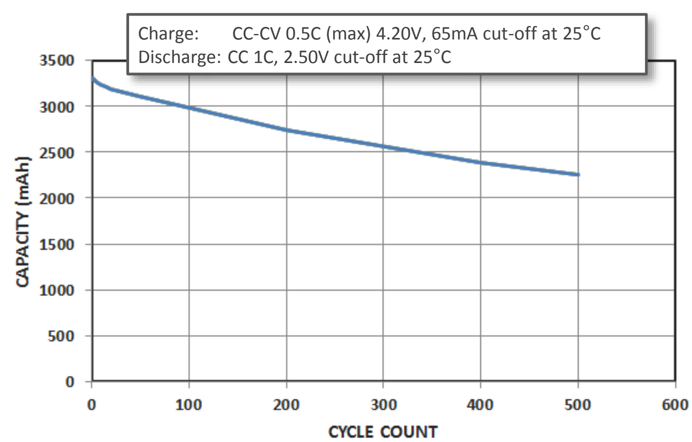


For Reference Only

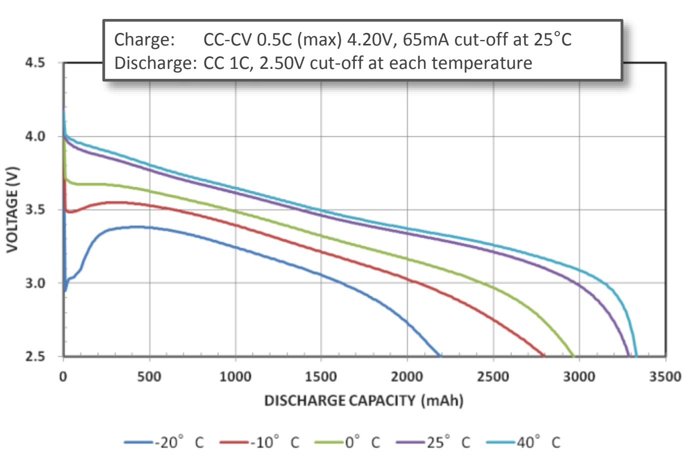
Charge Characteristics



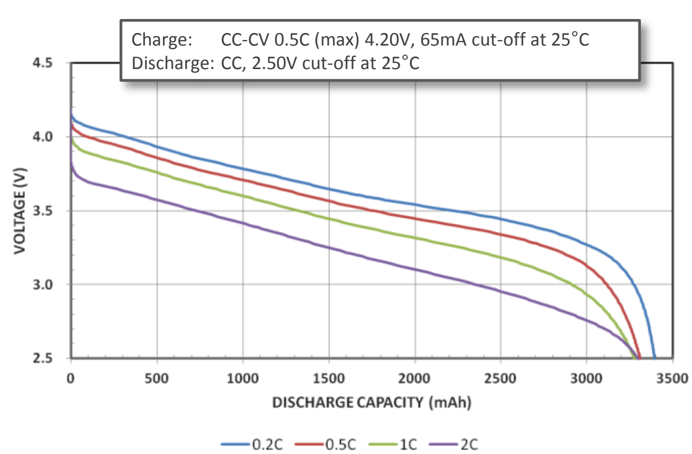
Cycle Life Characteristics



Discharge Characteristics (by temperature)



Discharge Characteristics (by rate of discharge)



The data in this document is for descriptive purposes only and is not intended to make or imply any guarantee or warranty.

For more information on how Panasonic can assist you with your battery power solution needs, visit us at www.panasonic.com/industrial/batteries-oem, e-mail secsales@us.panasonic.com, or call (469) 362-5600.

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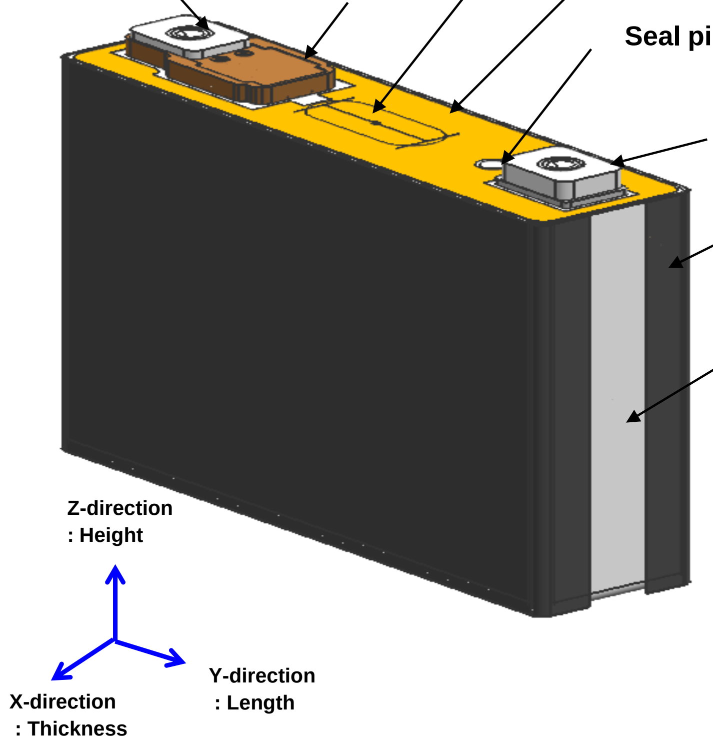
A.2 Samsung SDI 94Ah prismatic Cell, datasheet and characteristics

Introduction of Samsung SDI's 94Ah cells

31th Dec. 2015

SAMSUNG SDI SAMSUNG

Cell Appearance
94Ah(1)



Items	Characteristics
Cell Height (Z)	125mm
Cell Total height (Z)	133mm (Rivet)
Cell Length (Y)	173mm
Cell Thickness (X)	45mm

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SAMSUNG SDI SAMSUNG

Summary of cell performance

Cell type					94Ah cell
Energy	Capacity (min.)		1/3C rate, 25°C, Discharge	Ah	94
	Energy (min.)		1/3C rate, 25°C, Discharge	Wh	345
	Specific energy (min.)			Wh/kg	165
General information	Nominal voltage		-	V	3.68
	Size		Width x height x Thickness	mm	173 x 125 x 45
	Cell weight (max.)		Bare cell	kg	2.1
	Operating voltage		-	V	2.7 ~ 4.15
	Operating temperature		-	°C	-40 ~ 60
Operation current	Discharge	Continuous	25°C	A	150
		Peak	25°C	A	409
	Charge	Continuous	25°C	A	72
		Peak	25°C	A	270
Power capability	5sec discharge	Resistance	RT, 50% SOC	mOhm	0.75
		Specific power capability	RT, 50% SOC (at V_min)	W	3,500
	30sec discharge	Resistance	RT, 50% SOC	mOhm	0.99
		Specific power capability	RT, 50% SOC (at V_min)	W	2,600
Life	Cycle life		0.5C/1C, RT, EOL80%/EOL70%	cycles	3,200 / 5,200
			1C/1C, 45°C, EOL80%/EOL70%	cycles	1,500 / 2,500
	Calendar life		SOC100%, 25°C, EOL80%/EOL70%	years	17 / 26
Swelling force	Max. force at EOL		0.5C/1C, RT, rigid jig	N	< 25000
China homologation			GB/T certificate	PASS	PASS estimation
Transportation			UN 38.9	PASS	PASS estimation

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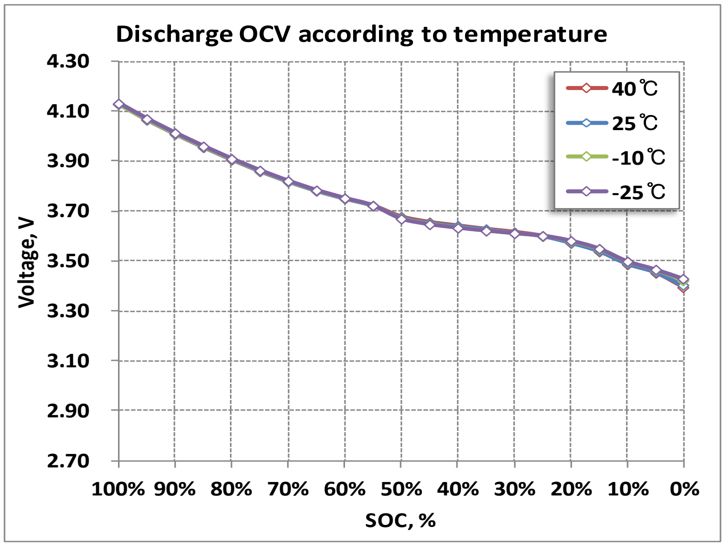
Discharge OCV

5% interval at 25℃/ -25℃



- **Discharge method**

1.Standard charge at RT (SOC = 100%), rest 3 hrs
2.Temperature change (25℃ to -25℃)
3.Soaking(5h), rest 1hr
4. Room Temperature Change (-25℃ to 25℃, soaking 2hrs)
5.Adjustment of SOC: Discharge by 5% SOC with 1/3C , rest 3 hrs
6.Repeat step 2~5 until SOC=0% or until to meet limit voltage

OCV	Discharge @ 40℃	Discharge @ 25℃	Discharge @ -10℃	Discharge @ -25 ℃
100%	4.129	4.129	4.131	4.132
90%	4.009	4.010	4.012	4.013
80%	3.9076	3.907	3.909	3.910
70%	3.818	3.819	3.820	3.821
60%	3.750	3.751	3.751	3.752
50%	3.677	3.676	3.671	3.669
40%	3.641	3.641	3.634	3.647
30%	3.616	3.614	3.611	3.611
20%	3.572	3.574	3.579	3.581
10%	3.452	3.490	3.496	3.499
0%	3.395	3.404	3.422	3.429

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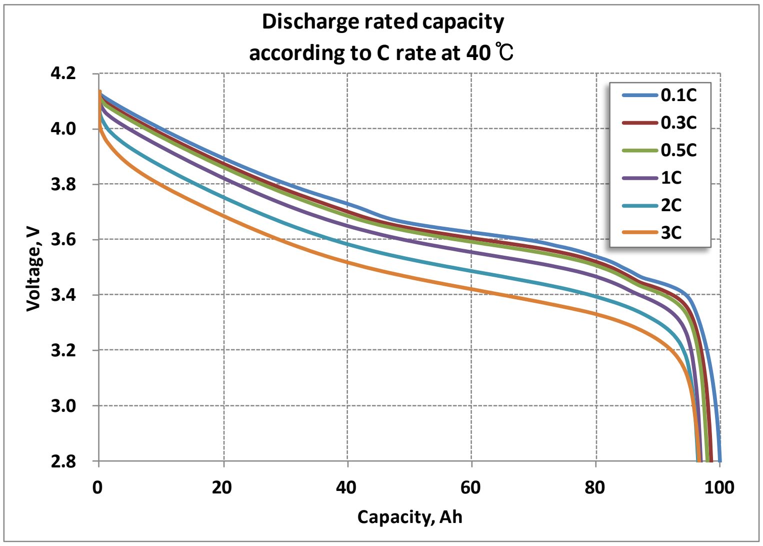
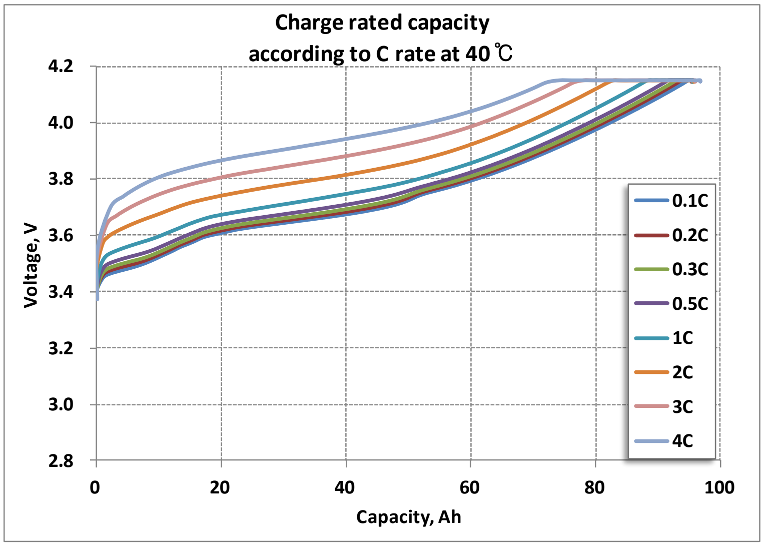
Rated Capacity

0.1C ~4C rates @ 40℃





C-rate		0.1C	0.3C	0.5C	1C	2C	3C
Discharge	Capacity	100.2 Ah	98.8 Ah	98.1 Ah	97.0 Ah	96.6 Ah	96.9 Ah
	% (vs.1/3C)	101.40%	100.00%	99.30%	98.20%	97.80%	98.10%
	Energy (Wh)	370 Wh	363 Wh	360 Wh	352 Wh	345 Wh	339 Wh
	% (vs.1/3C)	101.80%	100.00%	99.00%	97.00%	94.90%	93.40%

C-rate		0.1C	0.2C	0.3C	0.5C	1C	2C	3C	4C
Charge (CC/CV)	Capacity	95.5 Ah	95.4 Ah	95.5 Ah	95.6 Ah	95.7 Ah	95.8 Ah	95.9 Ah	96.9 Ah
	% (vs.1/3C)	100.00%	99.90%	100.00%	100.10%	100.20%	100.30%	100.40%	101.50%
Charge (CC)	Capacity	94.8 Ah	93.7 Ah	92.4 Ah	91.6 Ah	88.2 Ah	81.8 Ah	76.5 Ah	72.2 Ah
	% (vs.1/3C)	102.60%	101.40%	100.00%	99.10%	95.40%	88.50%	82.80%	78.20%

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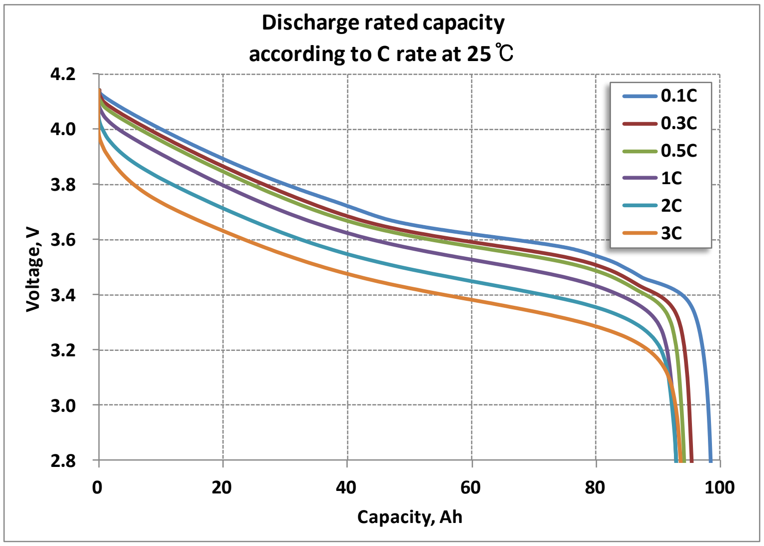
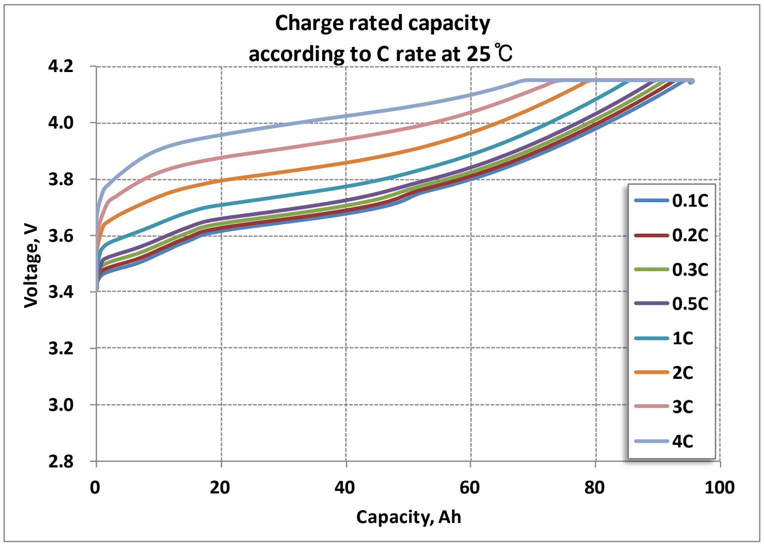
Rated Capacity

0.1C ~4C rates @ 25℃





C-rate		0.1C	0.3C	0.5C	1C	2C	3C
Discharge	Capacity	98.6 Ah	95.5 Ah	94.4 Ah	93.1 Ah	93.2 Ah	93.9 Ah
	% (vs.1/3C)	103.30%	100.00%	98.80%	97.50%	97.60%	98.40%
	Energy (Wh)	365 Wh	351 Wh	346 Wh	337 Wh	330 Wh	326 Wh
	% (vs.1/3C)	103.80%	100.00%	98.40%	95.90%	94.00%	92.80%

C-rate		0.1C	0.2C	0.3C	0.5C	1C	2C	3C	4C
Charge (CC/CV)	Capacity	95.3 Ah	95.1 Ah	95.1 Ah	95.1 Ah	95.2 Ah	95.3 Ah	95.5 Ah	95.6 Ah
	% (vs.1/3C)	100.20%	100.00%	100.00%	100.00%	100.00%	100.20%	100.40%	100.50%
Charge (CC)	Capacity	94.2 Ah	92.4 Ah	90.8 Ah	89.2 Ah	85.0 Ah	78.6 Ah	73.3 Ah	68.0 Ah
	% (vs.1/3C)	103.70%	101.80%	100.00%	98.30%	93.60%	86.60%	80.70%	74.90%

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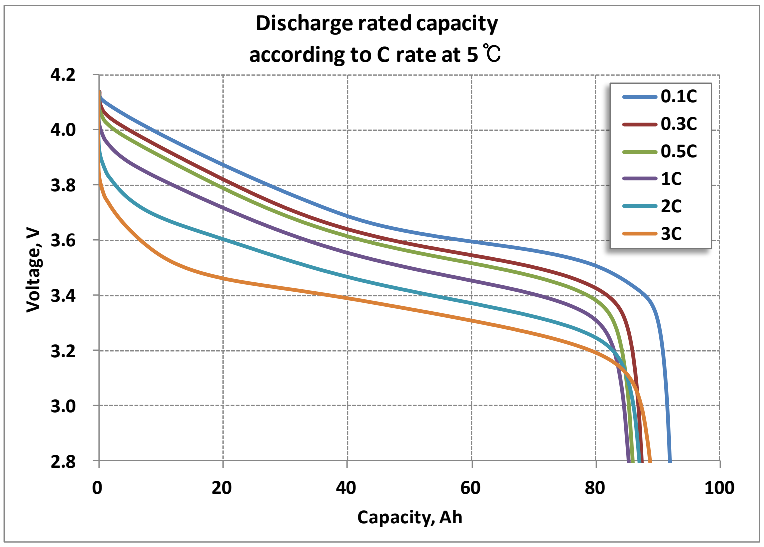
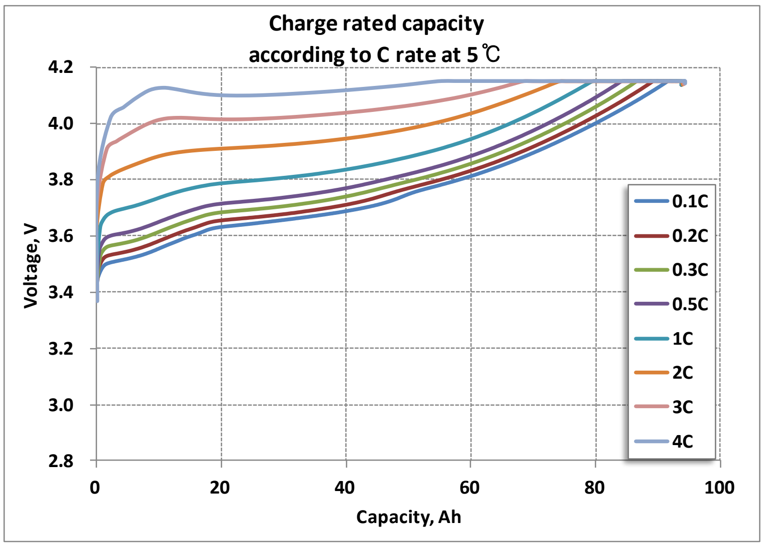
Rated Capacity

0.1C ~4C rates @ 5℃





C-rate		0.1C	0.3C	0.5C	1C	2C	3C
Discharge	Capacity	92.1 Ah	87.5 Ah	86.2 Ah	85.6 Ah	87.5 Ah	89.2 Ah
	% (vs.1/3C)	105.30%	100.00%	98.60%	97.80%	100.00%	101.90%
	Energy (Wh)	340 Wh	320 Wh	313 Wh	305 Wh	303 Wh	301 Wh
	% (vs.1/3C)	106.50%	100.00%	97.90%	95.50%	94.80%	94.00%

C-rate		0.1C	0.2C	0.3C	0.5C	1C	2C	3C	4C
Charge (CC/CV)	Capacity	93.8 Ah	93.7 Ah	93.7 Ah	93.7 Ah	93.8 Ah	94.0 Ah	94.3 Ah	94.3 Ah
	% (vs.1/3C)	100.10%	100.00%	100.00%	100.00%	100.00%	100.30%	100.60%	100.60%
Charge (CC)	Capacity	91.6 Ah	88.9 Ah	86.6 Ah	84.0 Ah	79.1 Ah	73.3 Ah	65.3 Ah	53.1 Ah
	% (vs.1/3C)	105.80%	102.70%	100.00%	97.10%	91.40%	84.70%	75.50%	61.40%

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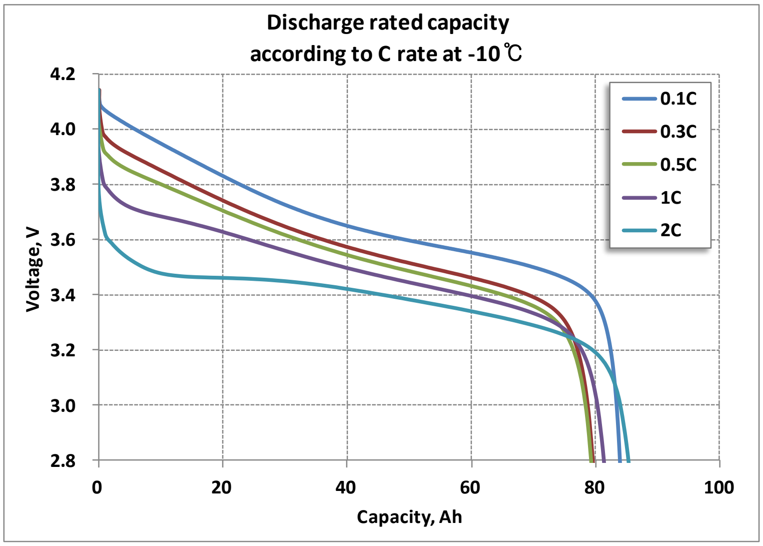
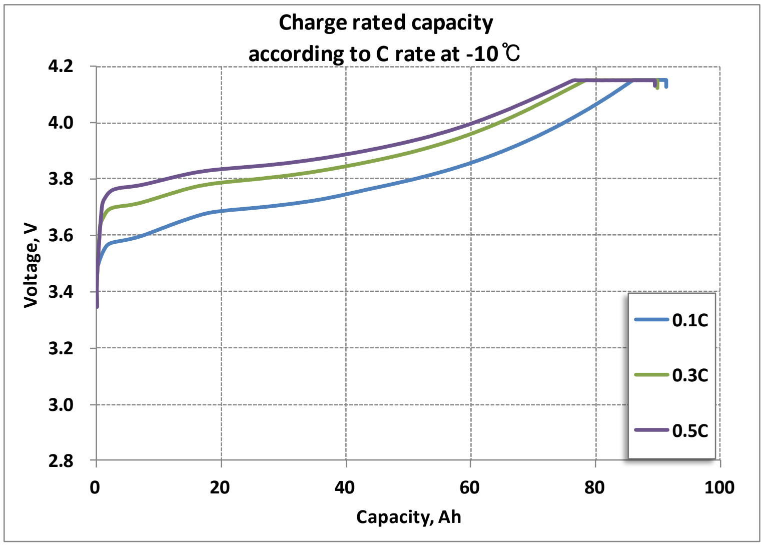
Rated Capacity

0.1C ~2C rates @ -10℃





C-rate		0.1C	0.3C	0.5C	1C	2C
Discharge	Capacity	84.2 Ah	79.9 Ah	79.7 Ah	81.7 Ah	85.7 Ah
	% (vs.1/3C)	105.40%	100.00%	99.80%	102.20%	107.30%
	Energy (Wh)	309 Wh	287 Wh	283 Wh	285 Wh	289 Wh
	% (vs.1/3C)	107.70%	100.00%	98.90%	99.40%	101.00%

C-rate		0.1C	0.3C	0.5C
Charge (CC/CV)	Capacity	91.4 Ah	89.9 Ah	89.5 Ah
	% (vs.1/3C)	101.70%	100.00%	99.60%
Charge (CC)	Capacity	86.0 Ah	77.9 Ah	75.8 Ah
	% (vs.1/3C)	110.50%	100.00%	97.30%

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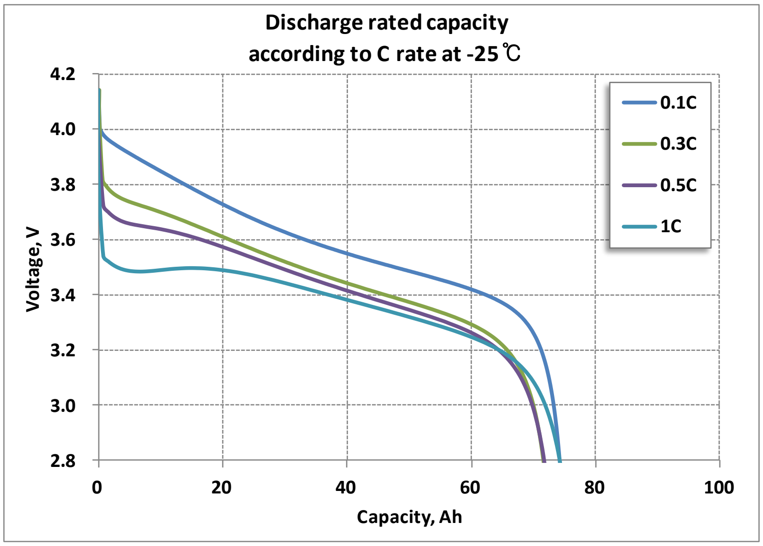
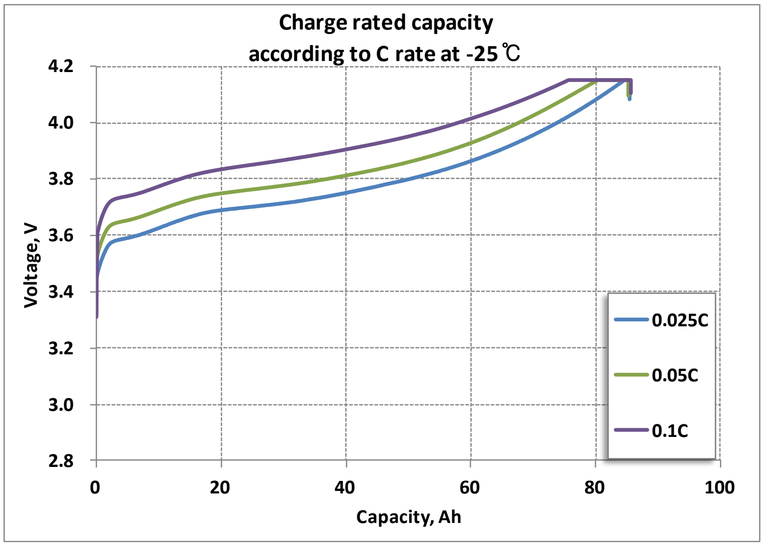
Rated Capacity

0.025C ~1C rates @ -25℃





C-rate		0.1C	0.3C	0.5C	1C
Discharge	Capacity	74.6 Ah	72.0 Ah	72.3 Ah	75.0 Ah
	% (vs.1/3C)	96.50%	100.00%	100.40%	104.10%
	Energy (Wh)	267 Wh	250 Wh	248 Wh	252 Wh
	% (vs.1/3C)	93.40%	100.00%	99.30%	100.80%

C-rate		0.025C	0.05C	0.1C
Charge (CC/CV)	Capacity	85.5 Ah	85.3 Ah	85.6 Ah
	% (vs.1/3C)	113.40%	113.00%	100.00%
Charge (CC)	Capacity	84.7 Ah	80.4 Ah	75.4 Ah
	% (vs.1/3C)	112.30%	106.50%	100.00%

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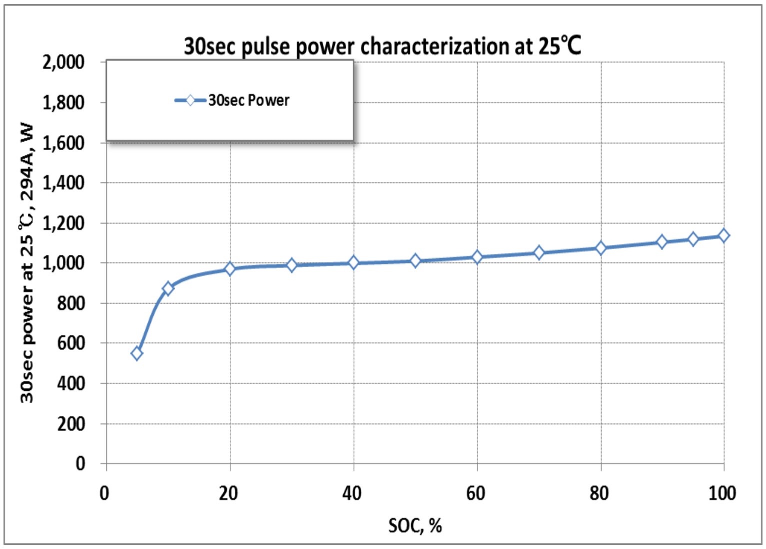
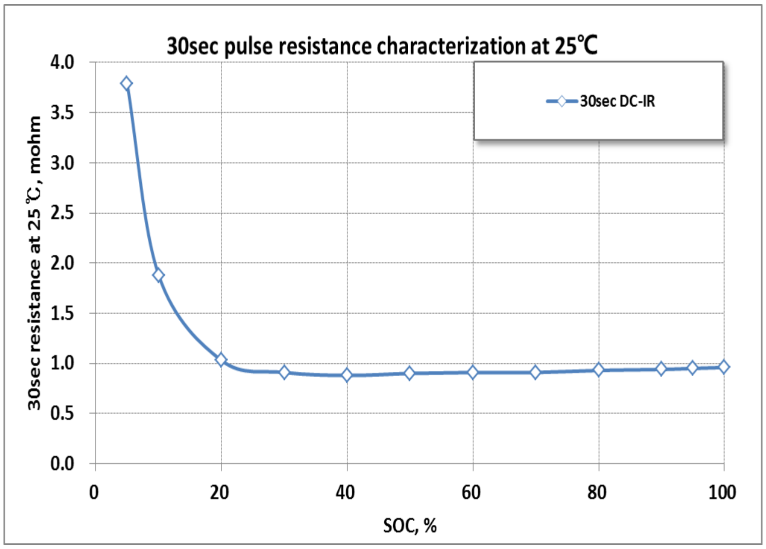
Power and DC-IR

@ 30sec discharge, 25℃, 294A





	SOC (%)	100	95	90	80	70	60	50	40	30	20	10	5	Max current
Discharge	Resistance (mΩ)	0.96	0.95	0.94	0.93	0.91	0.91	0.90	0.88	0.91	1.03	1.88	3.79	294 A
	Power (W)	1135	1119	1104	1075	1050	1030	1010	999	988	969	873	550	

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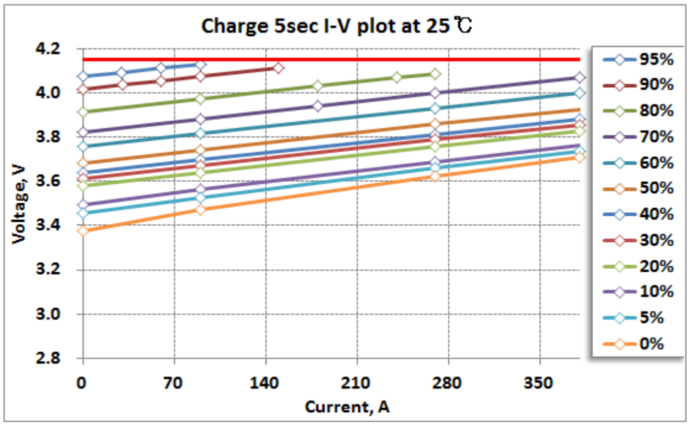
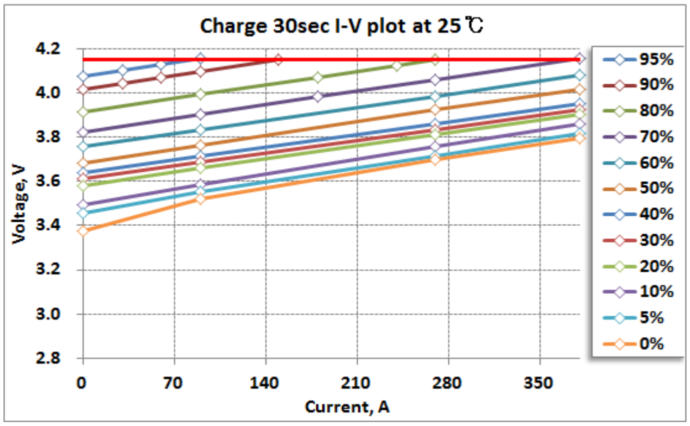
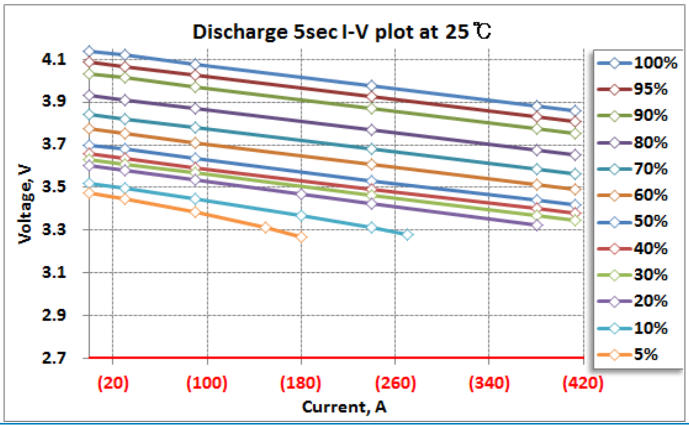
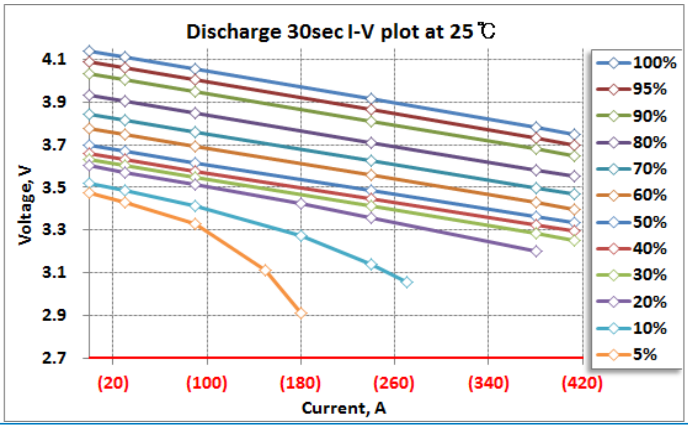
Pulse power characterization test

I-V plot at 5sec, 30sec at 25℃









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Safety current limit

Charge and Discharge

Temperature (℃)	Safety Current Limit			
	Discharge		Charge	
	I_{max} (safety)	max. allowed duration (msec)	I_{max} (safety)	max. allowed duration (msec)
60	500	700	360	700
50	500	700	360	700
40	500	700	360	700
35	500	700	360	700
30	500	700	360	700
25	500	700	360	700
20	500	700	360	700
15	500	700	360	700
10	500	700	360	700
5	500	700	360	700
0	500	700	360	700
-5	500	700	245	700
-10	500	700	165	700
-15	500	700	83	700
-20	500	700	45	700
-25	500	700	30	700
-30	500	700	9.4	700
-40	500	700	1.8	700

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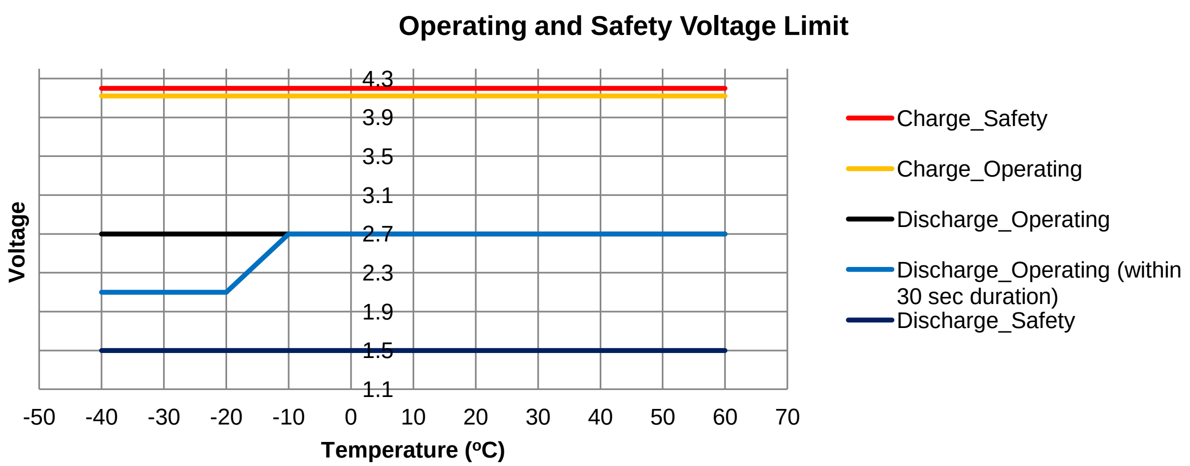
Operating and safety voltage limit

Charge and Discharge

	Item	Value	Remark
Safety limit	Charge	4.25 V	
	Discharge	1.5 V	
Operating limit	Charge	4.15 V	
	Discharge	2.7 V	2.1 V at below -20°C within 30 sec duration



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Operating and safety temperature limit

Operating and storage

	Item	Value	Remark
Safety limit	Maximum storage	80°C	This is to be ensured in an ambient temperature range (Electrolyte gas generation, OSD deformation vent opening, leakage, etc.)
	Minimum storage	-40°C	This is to be ensured in an ambient temperature range
	Maximum operation	80°C	This is to be ensured in a cell core temperature
	Minimum operation	-40°C	This is to be ensured in a cell core temperature
Operation limit	Maximum operation	60°C	This is to be ensured in a cell core temperature
	Minimum operation	-40°C	This is to be ensured in a cell core temperature

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A.3 Weiss Tehcnik chamber

weisstechnik®
a schunk company

Test Systems for Electrical Energy Storage

Illustration is similar, contains optional equipment

weisstechnik vötschtechnik

www.weiss-technik.com

Know-how for e-mobility – at full charge.

E-mobility is a worldwide automobile mega trend. In the field of mobile systems, lithium-ion batteries have successfully prevailed as energy storage device. Ever larger applications – such as electric vehicles – require storage systems, which not only offer a large energy content, but can also produce large power outputs. Specially designed for lithium-ion batteries, Weiss Technik offers reliable and safe solutions for most diverse test requirements. Test us.

All tests from a single source.

State-of-charge temperature and climate tests are carried out routinely to test the safety, reliability and performance of energy storage devices. Depending on the testing task, it might also be important to carry out further tests. That is why we offer our customers solutions to test various environmental factors, including extreme thermal, climatic and mechanical impacts.

Test equipment in all dimensions.

Depending on the testing task, it can be required to test individual cells, modules and battery packs or complete drive units with a Battery Management System (BMS). Our large selection of tried and tested standard test chambers is already well-equipped in series or will gladly be individually modified for you. Beyond that, we also plan and realise custom test chambers and rooms for entire drive units as a single-source provider.

Better test safely.

Laboratory hazards.

Testing lithium-ion packs, modules and cells with their increasing energy densities is a sensitive topic. During the temperature tests, overchargings or malfunctions of the batteries may occur. This can lead to the destruction of the batteries. Increasing storage sizes cause increasing impacts of possible failures and potential risks during tests with lithium-ion batteries. For this reason, safety in the laboratory, in particular the protection of the staff during such tests has the highest priority.

Framework conditions for energy storage tests.

Although there are binding specifications concerning battery tests for electric vehicles, it is crucial to have an experienced partner at your side who understands the requirements of battery testing. As TÜV-certified specialist for battery testing technology, we are therefore guided by the Machinery Directive and the requirements of the CE Declaration of Conformity. Furthermore, we take into account the ATEX directives and the EUCAR Hazard Standards for hazard assessment.

Tests under the influence of temperature		
External influences, such as	• External heating • Overcharging • Deep discharge • Excessive charging current • External short-circuit	**Internal events, such as** • Electrode electrolyte reactions • Electrochemical reactions
Impacts on the lithium-ion battery		
Hazard Level	Description	Classification criteria and effect
0	No effect	No effect. No loss of functionality.
1	Passive protection activated	No defect; no leakage; no venting, fire or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	Defect/damage	No leakage; no venting, fire or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	Leakage Δ mass < 50 %	No venting, fire or flame*; no rupture; no explosion. Weight loss < 50 % of electrolyte weight (electrolyte = solvent + salt).
4	Venting Δ mass ≥ 50 %	No fire or flame*, no rupture; no explosion. Weight loss ≥ 50 % of electrolyte weight (electrolyte = solvent + salt).
5	Fire or flame	No rupture; no explosion (i.e., no flying parts).
6	Rupture	No explosion, but flying parts of the active mass.
7	Explosion	Explosion (i.e. disintegration of the cell).

* The presence of flame requires the presence of an ignition source in combination with fuel and oxidizer in concentrations that will support combustion. A fire or flame will not be observed if any of these elements are absent. For this reason, we recommend that a spark source be used during tests that are likely to result in venting of cell(s). We believe that "credible abuse environments" would likely include a spark source. Thus, if a spark source was added to the test configuration and the gas or liquid expelled from the cell was flammable, the test sample would quickly progress from Hazard Level 3 or 4 to Hazard Level 5.
Source: Own illustration based on EUCAR

Best equipped as standard.

Comprehensive in basic configuration and accessories.

For an optimal protection of persons, test specimens, test equipment and the laboratory itself when testing electrical storage devices, our frequently tried and tested ClimeEvent and TempEvent standard test chambers are the best choice. They are easy to operate and available with test space volumes ranging from 40 to 2,000 litres. Here, a large selection of standard accessories is available to you.

Nearly limitless modifications.

Special testing tasks require special test chambers. This is why we modify the standard chambers according to the hazard assessment and requirement at hand. For example, by adding safety components such as a flushing device with a particularly high air replacement rate. In addition, we offer a wide range of special solutions, such as positioning the control technology above the test chamber, for heavy-duty gratings with a telescopic system and drawer systems for up to 12 batteries with a guide-through and plug-in connector panel.

Available safety equipment.

Safety equipment*	Hazard Levels				
	0-3	4	5	6	7
Status indicator	✔	✔	✔	✔	✔
Electrical door lock	✔	✔	✔	✔	✔
Reversible pressure release flap		✔	✔	✔	✔
Mechanical door lock		✔	✔	✔	✔
Sealing plug and retaining clamp		✔	✔	✔	✔
Particle blocker		✔	✔	✔	✔
Fire detection via CO gas measuring or temperature sensor			✔	✔	✔
Flushing device with N_2 or with CO_2			✔		
N_2 permanent inertisation				✔	✔
O_2 measuring unit				✔	✔
Burst disc					✔
Test system in overpressure-suitable design					✔

*For (modified) standard. Divergent safety equipment for special facilities. For further information please contact us.

weisstechnik vötschtechnik

Our innovative Test Chambers are available as **weiss**technik or **vötsch**technik.

Comprehensive safety accessories equipped as standard.

- **Status indicator**

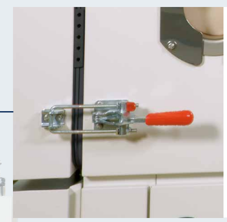
The signal lamp can be positioned variably on the device due to an adjustable magnetic foot. The red signal lamp flashes when a fault occurs. In addition, an acoustic signal is possible.

- **Reversible pressure release flap**

The venting duct is installed on the top of the cabinet. It is equipped with a mechanical, weighted pressure release flap. This can be dimensioned from 80 to 200 mm in diameter, depending on the expected volume of escaping gas.

- **Electrical door lock**

The test space door is locked via an electrical door lock during automatic and manual tests. In automatic mode the complete testing system can be switched off during a program interruption, in order to allow the unlocking of the test space door.



- **Mechanical door lock**

Two fasteners which mechanically hold the door closed are attached to the test space door in addition to the reversible pressure release flap.

- **Sealing plug and retaining clamp**

The entry ports are equipped with retaining clamps to secure the plug.

- **Fire detection via temperature measuring**

Fire is detected by an independent, freely movable Pt 100 temperature sensor. The sensor records temperature increases which are possibly caused by fire inside the test cabinet.

Our innovative Test Chambers are available as **weiss**technik or **vötsch**technik.

Numerous modifications.

- **N_2 permanent inertisation**

The door lock is activated for permanent inerting of the test space with nitrogen (N_2) or argon (Ar). A major flushing quantity reduces the oxygen concentration to ≤ 5 %. After the minimum flushing time has elapsed, testing is released and the system switches to a process-orientated small flushing quantity.

- **O_2 measuring unit**

In combination with the permanent inertisation using nitrogen or argon, the oxygen (O_2) measurement is used to monitor the O_2 concentration in the test space. It allows a controlled infeed of nitrogen or argon.

- **Fire detection via CO gas measuring**

Detection of fire using a carbon monoxide (CO) measurement. An electrochemical sensor is used to measure the CO in the air with the help of a gas measuring pump and tempering of the sample gas. Contacts for alarms are made available on the test cabinet. In conjunction with this option, hydrocarbon (CH) and hydrogen monitoring (H_2) is also possible.

- **Flushing device for inertisation in case of fire**

When a fire is detected, the test space can be flooded with nitrogen (N_2) or carbon dioxide (CO_2). This flooding inertises the test space and with liquid CO_2 also has a slight cooling effect.

- **CO_2-compressed gas bottles**

As an addition to the flushing device for inertisation in case of fire, a compressed gas bottle, filled with 7.5 kg CO_2 and an aromatic additive, is attached to the side of the test cabinet. The CO_2 is filled into the test space in a liquid state. When it expands, cold gas and CO_2 snow is formed. Several bottles can be cascaded. Manual triggering is also possible.

- **Pressure reduction unit using certified burst disc**

In case of damage to the battery, large volumes of gas can be released into the test space at a blow. To extract the gas rapidly, the chamber can be equipped with a pressure release system, connected to a waste air duct. For this, the test space container is manufactured in an overpressure-suitable design and a burst disc is integrated into the ceiling.

Our innovative Test Chambers are available as **weiss**technik or **vötsch**technik.

Maybe a bit bigger?

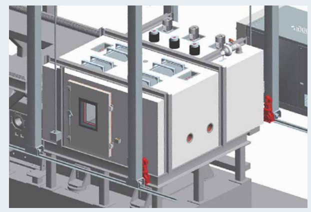
Always the right solution.

If the standard test chambers are not large enough for you or the test requirements call for a special solution, Weiss Technik offers you almost unlimited options. As a single-source supplier, we develop and implement test chambers and test rooms for modules, packs and complete drive units, with or without BMS. In terms of size, you have choices ranging from walk-in test chambers up to test rooms for entire vehicles.

We offer almost the entire range of battery tests. This includes temperature and climate tests, dust, corrosion and temperature shock tests, splash water tests as well as immersion tests. In addition, our programme includes test systems for damp heat tests, vibration tests and multi-axial shaker tables (MAST).

Worldwide unique.

In order to test really large battery packs under high loads, we have built a new and spectacular testing system, for example. The 17-m³ test room combines a climate test with special dynamic load tests and the capability of flooding the test chamber.



Realistic testing under harsh conditions.

Even large battery packs have to be tested under the most extreme conditions. That is why we built a testing system to dust entire vehicles. With this system, we can test which effects dust has on the batteries under different climatic conditions and where their potential weak points may lie.

Flexible in all directions.

The 14-m³ test chamber was designed for a combined temperature vibration test with a multi-axial shaker table. The distinguishing features of this test system are the flexible, insulated test chamber walls, which can be raised and lowered by motor.

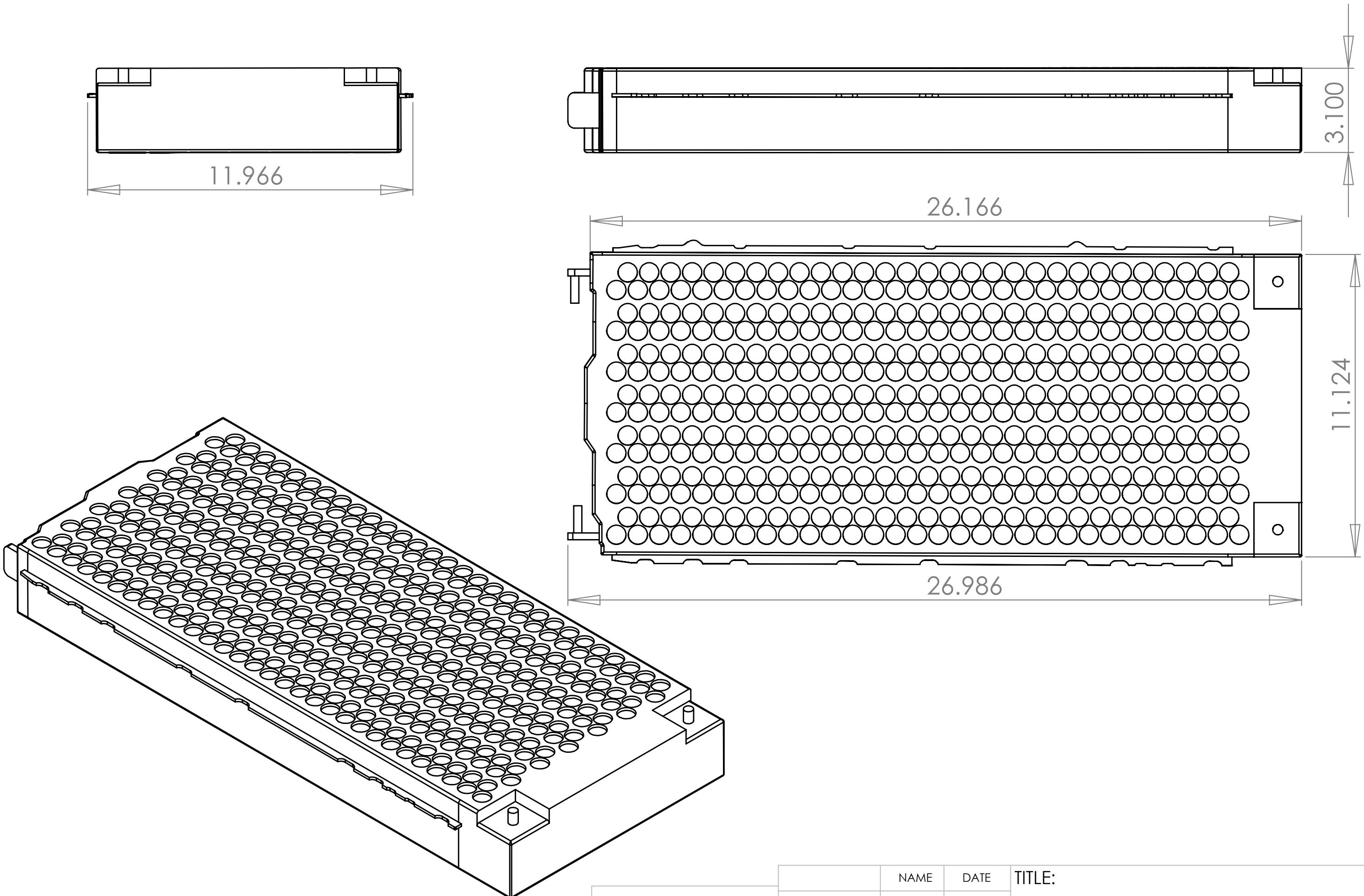
A.4 Tesla Model S battery module

Specifications

Capacity (ideal)	5.2 kWh (233 Ah)
Module Energy Density	198 Wh/kg
Discharge Current (max, 3s)	1,520 A (~6.5C)
Discharge Current (10s)	1,000 A (~4.3C)
Discharge Current (continuous)	233 A (~1C)
Discharge Power (max, 3s)	30 kW
Discharge Power (continous)	5 kW
Charge Power (max, 10m)	8 kW
Charge Power (continous)	5 kW
Cell Configuration	6 series of 74 parallel (6s74p) 444 cells
Weight	58 lbs (26.3 kg)
Dimensions (approximate)	27 x 12 x 3"
Voltage (nominal)	22.2 V
Voltage (max)	25.2 V
Voltage (minimum)	18 V
Cell type	Tesla Custom Panasonic 18650 (similar to NCR18650B)
Cooling	5/16" tubing (8mm) Required when (dis)charge >= 1C
Max operating Temp	60C / 140F
Min operating Temp	-18C / 0F
Min Temp. (charging)	4C / 41F (Charge rate should be limited at low temperatures)
Terminals	M8 bolts (13mm, included)

* NOTE: Actual battery capacity specifications may vary in real-world conditions and are listed here as a base reference for a new module and are for comparison purposes only. While we strive to sell the best possible battery modules, the Tesla battery modules we acquire are used and actual capacities are not guaranteed. They may vary based on the actual age, usage patterns, cycles, etc.

It is up to you to use these battery modules in a safe manner within their specifications. We explicitly disclaim any and all liability related to the use of these battery modules.



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TITLE:

DWG. NO.
Model S Batt
REV

SCALE: 1:10 WEIGHT: SHEET 1 OF 1

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A.5 teledyne lecroy wavesurfer 3014z

TELEDYNE LECROY
Everywhereyoulook™

BIGGEST TOUCH. BEST VALUE.

WaveSurfer 3000z

100 MHz – 1 GHz
Oscilloscopes

MAUI

- 10.1" Capacitive Touch Screen
- 20 Mpts Memory
- Powerful, Deep Toolbox

The WaveSurfer 3000z has a 10.1" capacitive touch display, the longest memory, and the deepest toolbox – all at an affordable price.

teledynelecroy.com/oscilloscope/wavesurfer-3000z-oscilloscopes

SPECIFICATIONS

Analog - Vertical

	WaveSurfer 3014z	WaveSurfer 3024z	WaveSurfer 3034z	WaveSurfer 3054z	WaveSurfer 3104z
Analog Bandwidth @ 50Ω (-3dB)	100 MHz	200 MHz	350 MHz	500 MHz	1 GHz
Rise time	3.5 ns (typical)	1.75 ns (typical)	1 ns (typical)	800 ps (typical)	430 ps (typical)
Input Channels	4				
Vertical Resolution	8-bits; up to 11-bits with enhanced resolution (ERES)				
Sensitivity	50 Ω: 1mV/div - 1 V/div; 1 MΩ: 1 mV/div - 10 V/div				
DC Gain Accuracy	±(1.5%) Full Scale, Offset at 0V, > 5mV/div; ±(2.5%) < 5 mV/div				
BW Limit	20 MHz		20 MHz, 200 MHz		
Maximum Input Voltage	50 Ω: 5 Vrms, ±10 V Peak; 1 MΩ: 400 V max (DC + Peak AC ≤ 10 kHz)				
Input Coupling	50 Ω: DC, GND; 1 MΩ: AC, DC, GND				
Input Impedance	50 Ω ±2.0%, 1 MΩ ±2.0% || 16 pF				
Offset Range	50 Ω: 1 mV - 19.8 mV: ±2 V, 20 mV - 100 mV: ±5 V, 102 mV - 198 mV: ±20 V, 200 mV - 1 V: ±50 V 1 MΩ: 1 mV - 19.8 mV: ±2 V, 20 mV - 100 mV: ±5 V, 102 mV - 198 mV: ±20 V, 200 mV - 1 V: ±50 V, 1.02 V - 1.98 V: ±200 V, 2 V - 10 V: ±400 V				
Offset Accuracy	±(1.0% of offset value + 1.5%FS + 1 mV)				

Analog - Acquisition

	WaveSurfer 3014z	WaveSurfer 3024z	WaveSurfer 3034z	WaveSurfer 3054z	WaveSurfer 3104z
Sample Rate (Single-shot)	1 GS/s (2 GS/s interleaved)	2 GS/s (4 GS/s interleaved)			
Sample Rate (Repetitive)	50 GS/s				
Standard Memory (4 Ch / 2 Ch)	10 Mpts / 20 Mpts				
Acquisition Modes	Real Time, Roll, RIS (Random Interleaved Sampling), Sequence (Segmented Memory up to 1,000 segments with 1µs minimum intersegment time)				
Real Time Timebase Range	5 ns/div - 100 s/div	2 ns/div - 100 s/div		1 ns/div - 100 s/div	500 ps/div - 100 s/div
RIS Mode Timebase Range	5 ns/div - 10 ns/div	2 ns/div - 10 ns/div		1 ns/div - 10 ns/div	500 ps/div - 10 ns/div
Roll Mode Timebase Range	Up to 100 s/div (roll mode is user selectable at ≥ 50 ms/div)				
Timebase Accuracy	±10 ppm measured over > 1ms interval				

Digital - Vertical and Acquisition (WS3K-MSO Option Only)

Input Channels	16 Digital Channels
Threshold Groupings	Pod 2: D15 - D8, Pod 1: D7 - D0
Threshold Selections	TTL(+1.4V), 5V CMOS (+2.5V), ECL (-1.3V) or User Defined
Maximum Input Voltage	±30V Peak
Threshold Accuracy	±(3% of threshold setting + 100mV)
Input Dynamic Range	±20V
Minimum Input Voltage Swing	500mVpp
Input Impedance (Flying Leads)	100 kΩ || 5 pF
Maximum Input Frequency	125 MHz
Sample Rate	500 MS/s
Record Length	10MS - 16 Channels
Minimum Detectable Pulse Width	4 ns
Channel-to-Channel Skew	± (1 digital sample interval)
User defined threshold range	±10V in 20mV steps

Trigger System

Modes	Auto, Normal, Single, Stop
Sources	Any input channel, External, Ext/5, or line; slope and level unique to each source (except for line trigger)
Coupling	DC, AC, HFREJ, LFREJ
Pre-trigger Delay	0-100% of full scale
Post-trigger Delay	0-10,000 Divisions
Hold-off	10ns up to 20s or 1 to 100,000,000 events
Internal Trigger Level Range	±4.1 Divisions
External Trigger Level Range	Ext: ±610mV, Ext/5: ±3.05V
Trigger Types	Edge, Width, Logic (Pattern), TV (NTSC, PAL, SECAM, HDTV - 720p, 1080i, 1080p), Runt, Slew Rate, Interval (Signal or Pattern), Dropout, Qualified (State or Edge); External and Ext/5 support edge trigger only.

Measure, Zoom and Math Tools

Measurement Parameters	Up to 6 of the following parameters can be calculated at one time on any waveform: Amplitude, Area, Base, Delay, Duty Cycle, Fall Time (90%–10%), Fall Time (80%–20%), Frequency, Maximum, Mean, Minimum, Overshoot+, Overshoot-, Peak-Peak, Period, Phase, Rise Time (10%–90%), Rise Time (20%–80%), RMS, Skew, Standard Deviation, Top, Width+, Width-. Statistics and histicons can be added to measurements. Measurements can be gated.
Zooming	Use front panel QuickZoom button, or use touch screen or mouse to draw a box around the zoom area.
Math Functions	Up to 2 of the following functions can be calculated at one time: Sum, Difference, Product, Ratio, Absolute Value, Average, Derivative, Enhanced Resolution, Envelope, Floor, Integral, Invert, Reciprocal, Rescale, Roof, SinX/x, Square, Square Root, Trend, Zoom and FFT (up to 1 Mpts with power spectrum output and rectangular, VonHann, and FlatTop windows).

Probes

	WaveSurfer 3014z	WaveSurfer 3024z	WaveSurfer 3034z	WaveSurfer 3054z	WaveSurfer 3104z
Standard Probes	One PP019 (5mm) per channel		One PP020 (5mm) per channel		
Probing System	BNC and Teledyne LeCroy ProBus for Active voltage, current and differential probes				

SPECIFICATIONS

	WaveSurfer 3014z	WaveSurfer 3024z	WaveSurfer 3034z	WaveSurfer 3054z	WaveSurfer 3104z

Display System

Display Size	10.1" widescreen capacitive touch screen
Display Resolution	1024 x 600

Connectivity

Ethernet Port	10/100Base-T Ethernet interface (RJ-45 connector)
Removable Storage	(1) MicroSD Port - 16 GB micro SD card installed standard
USB Host Ports	(4) USB 2.0 Ports Total – (2) Front USB 2.0 Ports
USB Device Port	(1) USBTMC
GPIB Port (Optional)	Supports IEEE – 488.2
External Monitor Port	Standard DB-15 connector (support resolution of 1024x600)
Remote Control	Via Windows Automation, or via Teledyne LeCroy Remote Command Set
Network Communication Standard	VICP and LXI compatible

Power Requirements

Voltage	100 - 240 VAC ± 10% at 50-60 Hz +/-5%; 100 - 120 VAC ± 10% at 400 Hz +/- 5%; Automatic AC Voltage Selection
Power Consumption (Nominal)	80 W / 80 VA
Power Consumption (Max)	150 W / 150 VA (with all PC peripherals, digital leadset and active probes connected to 4 channels)

Environmental

Temperature	Operating: 0 °C to 50 °C; Non-Operating: -30 °C to 70 °C
Humidity	Operating: 5% to 90% relative humidity (non-condensing) up to ≤ 30 °C, Upper limit derates to 50% relative humidity (non-condensing) at +50 °C Non-Operating: 5% to 95% relative humidity (non-condensing) as tested per MIL-PRF-28800F
Altitude	Operating: 3,048 m (10,000 ft) max at ≤ 25C; Non-Operating: Up to 12,192 meters (40,000 ft)

Physical

Dimensions (HWD)	10.63"H x 14.96"W x 4.92"D (270 mm x 380 mm x 125 mm)
Weight	4.81 kg (10.6 lbs)

Regulatory

CE Certification	Low Voltage Directive 2014/35/EU; EN 61010-1:2010, EN 61010-2-030:2010 EMC Directive 2014/30/EU; EN 61326-1:2013, EN61326-2-1:2013; RoHS2 Directive 2011/65/EU
UL and cUL Listing	UL 61010-1, UL 61010-2-030:2010, 3rd Edition; CAN/CSA C22.2 No. 61010-1-12

Digital Voltmeter (optional)

Functions	AC_{rms}, DC, DC_{rms}, Frequency
Resolution	ACV/DCV: 4 digits, Frequency: 5 digits
Measurement Rate	100 times/second, measurements update on the display 5 times/second
Vertical Settings Autorange	Automatic adjustment of vertical settings to maximize the dynamic range of measurements

WaveSource Function Generator (optional)

General

Max Frequency	25 MHz
Channels	1
Sample Rate	125 MS/s
Arbitrary Waveform Length	16 kpts
Frequency Resolution	1 μHz
Vertical Resolution	14-bit
Vertical Range	±3V (HiZ); ±1.5V (50 Ω)
Waveform Types	Sine, Square, Pulse, Ramp, Noise, DC

Frequency Specification

Sine	1 μHz - 25 MHz
Square/Pulse	1 μHz - 10 MHz
Ramp/Triangular	1 μHz - 300 KHz
Noise	25 MHz (-3dB)
Resolution	1 μHz
Accuracy	±50 ppm, over temperature
Aging	±3 ppm/year, first year

Output Specification

Amplitude	4 mVpp - 6 Vpp (HiZ); 2 mVpp - 3 Vpp(50 Ω)
Vertical Accuracy	±(0.3dB + 1 mV)
Amplitude Flatness	±0.5dB

DC Offset

Range (DC)	±3V (HiZ); ±1.5V (50 Ω)
Offset Accuracy	±(1% of offset value + 3 mV)

Waveform Output

Impedance	50 Ω ± 2%
Protection	Short-circuit protection

Sine Spectrum Purity

SFDR (Non Harmonic) @1.265Vpp	
DC-1 MHz	-60dBc
1 MHz - 5 MHz	-55dBc
5 MHz - 25 MHz	-50dBc
Harmonic Distortion @1.265Vpp	
DC - 5 MHz	-50dBc
5 MHz - 25 MHz	-45dBc

Square/Pulse

Rise/fall time	24 ns (10% - 90%)
Overshoot	3% (typical - 1 kHz, 1 Vpp)
Pulse Width	50 ns min.
Jitter	500ps + 10ppm of period (RMS cycle to cycle)

Ramp/Triangle

Linearity	0.1% of Peak value output (typical - 1 kHz, 1 Vpp, 100% symmetric)
Symmetry	0% to 100%

ORDERING INFORMATION

Product Description	Product Code
WaveSurfer 3000z Oscilloscopes	
100 MHz, 2 GS/s, 4 Ch, 10 Mpts/Ch with 10.1" Capacitive Touch Screen Display 20 Mpts /Ch in interleaved mode	WaveSurfer 3014z
200 MHz, 4 GS/s, 4 Ch, 10 Mpts/Ch with 10.1" Capacitive Touch Screen Display 20 Mpts /Ch in interleaved mode	WaveSurfer 3024z
350 MHz, 4 GS/s, 4 Ch, 10 Mpts/Ch with 10.1" Capacitive Touch Screen Display 20 Mpts /Ch in interleaved mode	WaveSurfer 3034z
500 MHz, 4 GS/s, 4 Ch, 10 Mpts/Ch with 10.1" Capacitive Touch Screen Display 20 Mpts /Ch in interleaved mode	WaveSurfer 3054z
1 GHz, 4 GS/s, 4 Ch, 10 Mpts/Ch with 10.1" Capacitive Touch Screen Display 20 Mpts /Ch in interleaved mode	WaveSurfer 3104z

Included with Standard Configurations

÷10 Passive Probe (Total of 1 Per Channel), 1 Micro SD card (Installed), Micro SD card adapter, Protective Front Cover, Getting Started Guide, Commercial NIST Traceable Calibration with Certificate, Power Cable for the Destination Country, 3-year Warranty

Product Description	Product Code
General Accessories	
External GPIB Accessory	USB2-GPIB
Soft Carrying Case	WS3K-SOFTCASE
Rack Mount Accessory	WS3K-RACK
Local Language Overlays	
German Front Panel Overlay	WS3K-FP-GERMAN
French Front Panel Overlay	WS3K-FP-FRENCH
Italian Front Panel Overlay	WS3K-FP-ITALIAN
Spanish Front Panel Overlay	WS3K-FP-SPANISH
Japanese Front Panel Overlay	WS3K-FP-JAPANESE
Korean Front Panel Overlay	WS3K-FP-KOREAN
Chinese (Tr) Front Panel Overlay	WS3K-FP-CHNES-TR
Chinese (Simp) Front Panel Overlay	WS3K-FP-CHNES-SI
Russian Front Panel Overlay	WS3K-FP-RUSSIAN
Multi-Instrument Options	
MSO software option and 16 Channel Digital probe leadset	WS3K-MSO
MSO License (MS Probe Not Included)	WS3K-MSO-LICENSE
Function Generator Option	WS3K-FG
Audiobus Trigger and Decode Option for I²S, LJ, RJ, and TDM	WS3K-Audiobus TD
CAN and LIN Trigger and Decode Option	WS3K-AUTO
CAN FD Trigger and Decode Option	WS3K-CAN FDbus TD
I²C, SPI, UART and RS-232 Trigger and Decode Option	WS3K-EMB
FlexRay Trigger and Decode Option	WS3K-FlexRaybus TD
Power Analysis Option	WS3K-PWR
Probes	
250 MHz Passive Probe 10:1, 10 MΩ	PP019
500 MHz Passive Probe 10:1, 10 MΩ	PP020
700 V, 15 MHz High-Voltage Differential Probe	AP031

Product Description	Product Code
Probes (Cont'd)	
Power/Voltage Rail Probe. 4 GHz bandwidth, 1.2x attenuation, ±30V offset, ±800mV	RP4030
Browser for use with RP4030	RP4000-BROWSER
1,500 V, 120 MHz High-Voltage Differential Probe	HVD3106A
1kV, 80 MHz High Voltage Differential Probe with 6m cable	HVD3106A-6M
1kV, 120 MHz High Voltage Differential Probe without tip Accessories	HVD3106A-NOACC
1,500 V, 25 MHz High-Voltage Differential Probe	HVD3102A
1kV, 25 MHz High Voltage Differential Probe without tip Accessories	HVD3102A-NOACC
2kV, 120 MHz High Voltage Differential Probe	HVD3206A
2kV, 80 MHz High Voltage Differential Probe with 6m cable	HVD3206A-6M
6kV, 100 MHz High Voltage Differential Probe	HVD3605A
High Voltage Fiber Optic Probe, 60 MHz (requires accessory tip)	HVFO103
±1V (1x) Tip Accessory for HVFO103	HVFO100-1X-TIP
±5V (5x) Tip Accessory for HVFO103	HVFO100-5X-TIP
±20V (20x) Tip Accessory for HVFO103	HVFO100-20X-TIP
30 A; 100 MHz Current Probe – AC/DC; 30 A_{rms}; 50 A_{peak} Pulse	CP031
30 A; 100 MHz High Sensitivity Current Probe – AC/DC; 30 A_{rms}; 50 A_{peak} Pulse	CP031A
30 A; 50 MHz Current Probe – AC/DC; 30 A_{rms}; 50 A_{peak} Pulse	CP030
30 A; 50 MHz High Sensitivity Current Probe – AC/DC; 30 A_{rms}; 50 A_{peak} Pulse	CP030A
150 A; 10 MHz Current Probe – AC/DC; 150 A_{rms}; 500 A_{peak} Pulse	CP150
500 A; 2 MHz Current Probe – AC/DC; 500 A_{rms}; 700 A_{peak} Pulse	CP500
Deskew Calibration Source for CP031, CP030 and AP015	DCS025
500 MHz Differential Probe	AP033
200 MHz, 3.5 pF, 1 MΩ Active Differential Probe, ±20 V, 60V common-mode	ZD200
1 GHz, 1.0 pF, 1 MΩ Active Differential Probe, ±8 V, 10V common-mode	ZD1000
1.5 GHz, 1.0 pF, 1 MΩ Active Differential Probe, ±8 V, 10V common-mode	ZD1500
1 GHz, 0.9 pF, 1 MΩ High Impedance Active Probe	ZS1000
Set of 4 ZS1000	ZS1000-QUADPAK
1.5 GHz, 0.9 pF, 1 MΩ High Impedance Active Probe	ZS1500
Set of 4 ZS1500	ZS1500-QUADPAK
100:1 400 MHz 50 MΩ 1 kV High-voltage Probe	HVP120
100:1 400 MHz 50 MΩ 4 kV High-voltage Probe	PPE4KV
1000:1 400 MHz 50 MΩ 5 kV High-voltage Probe	PPE5KV
1000:1 400 MHz 50 MΩ 6 kV High-voltage Probe	PPE6KV
Probe Adapters	
TekProbe to ProBus Probe Adapter	TPA10
Set of 4 TPA10 TekProbe to ProBus Probe Adapters. Includes soft carrying case.	TPA10-QUADPAK

Customer Service

Teledyne LeCroy oscilloscopes and probes are designed, built, and tested to ensure high reliability. In the unlikely event you experience difficulties, our digital oscilloscopes are fully warranted for three years and our probes are warranted for one year. This warranty includes:

- No charge for return shipping
- Long-term 7-year support
- Upgrade to latest software at no charge

TELEDYNE LECROY
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1-800-5-LeCroy
teledynelecroy.com

Local sales offices are located throughout the world. Visit our website to find the most convenient location.

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A.6 Power meter PW3390

HIOKI

POWER ANALYZER PW3390

NEW

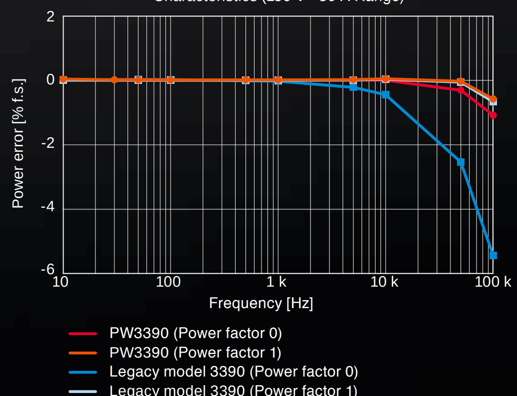
High Accuracy Power Analysis.
Anywhere, Anytime.

CE

Complete Pursuit of Measurement Accuracy and High Frequency Characteristics

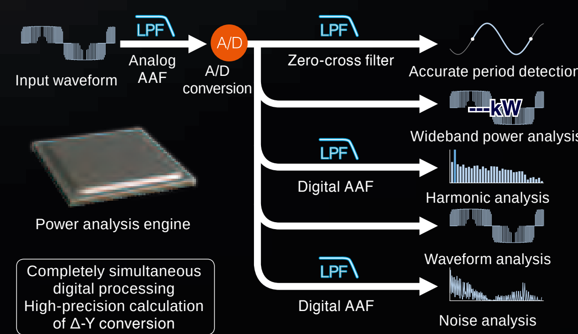
The PW3390 delivers 4 input channels and ±0.04% basic accuracy for power - the top instrument in its class. Achieve more precise measurements of the power and efficiency of high efficiency equipment used in power electronics. Further, a 200 kHz measurement band and flat amplitude and phase characteristics up to high frequencies enable the precise measurement of power at top frequency levels and low power factor.

Example of Active Power Frequency Characteristics (150 V - 50 A Range)



Power Analysis Engine That Achieves High-Speed Simultaneous Calculation on 5 Systems

Precisely capture input waveforms with 500 kS/s high-speed sampling and a high resolution 16-bit A/D converter. The power analysis engine performs independent digital processing for 5 systems: period detection, wideband power analysis, harmonic analysis, waveform analysis, and noise analysis. High-speed simultaneous calculation processing enables both precise measurements and a 50 ms data refresh rate.



* AAF (Anti-aliasing filter):
Filter that prevents aliasing errors during sampling

Current Sensors for the Thorough Pursuit of High Accuracy. Achieve Superior Accuracy for High-Frequency, Low Power Factor Power.

High Accuracy Sensor Pass-Through Type

Pass-through type with high accuracy and a wide measurement range. Conduct extremely accurate measurements of large currents to a maximum of 1000 A over a wide operating temperature range.

High Accuracy Sensor Clamp Type

Clamp for quick and easy connections. Conduct extremely accurate measurements of large currents to a maximum of 1000 A over a wide operating temperature range.

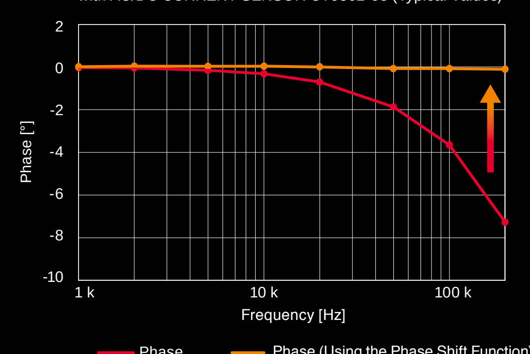
High Accuracy Sensor Direct Wire Type

Newly developed DCCT method delivers expansive measurement range and superior measurement accuracy at a rating of 50 A.

Built-in Current Sensor Phase Shift Function

Equipped with new virtual oversampling technology. Achieve phase shift equivalent to 200 MS/s while maintaining a high speed of 500 kS/s, as well as a high resolution of 16 bits. Set and correct the phase error of the current sensor at a resolution of 0.01°. Use of the phase shift function results in a dramatic reduction of measurement error. This allows the measurement of high-frequency, low-power factor power included in the switching frequency of inverter output, which is difficult to measure with conventional equipment.

Example of Phase Characteristic Compensation with AC/DC CURRENT SENSOR CT6862-05 (Typical Values)

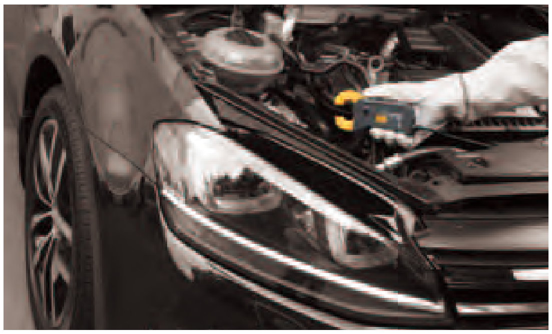


* Virtual oversampling:
Technology that uses a sampling frequency several hundred times higher than the actual sampling frequency to perform virtual deskewing

In the Laboratory or in the Field

Take Highly Accurate Measurements Even in Tough Temperature Conditions

Severe temperature environments, such as engine rooms with intense temperature changes and constant temperature rooms, can hinder high accuracy measurements. The extremely accurate pass-through and clamp type sensors both feature excellent temperature characteristics and a wide operation temperature range to help address these challenges.

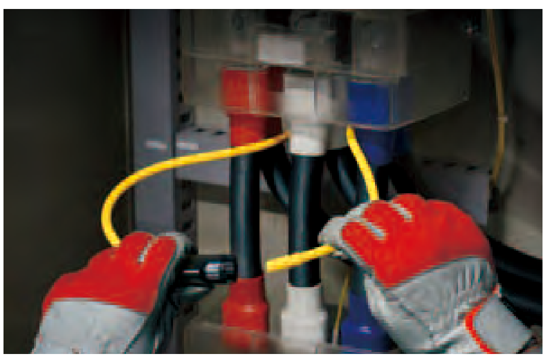


Achieve High Accuracy Measurement Even in the Field

Dramatically compact and light-weight form factor achieved by concentrating the calculation functions in the power analysis engine. Highly accurate measurements normally achieved in the laboratory are now also possible in the field.

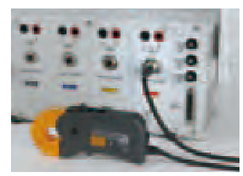
Max. 6000 A Measurement on 50 Hz/60 Hz Lines

The CT7040 AC FLEXIBLE CURRENT SENSOR series can measure commercial power lines up to 6000 A, including solar power conditioner output. Even thick cables can be wired easily among crowded wiring or in narrow locations.



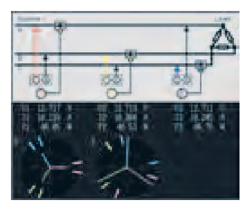
External Power Supply Not Needed for Sensor Connections

Power can be supplied to the current sensor from the main unit, so there is no need to provide a separate external power supply for the current sensor. Connected sensors are recognized automatically, for reliable and quick measurements.



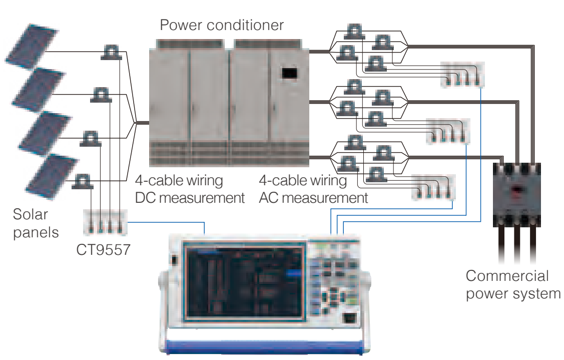
Wiring Displays and Quick Setup Lets You Begin Measuring Immediately

Perform wiring while checking wiring diagrams and vectors on the screen. Optimum settings are performed automatically simply by selecting a connection and using the quick setup function.



New Method for Measuring Large Current over Multi-Cable Wiring

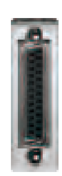
Highly accurate measurement of current in multi-cable wiring with large currents has been difficult-until now. The CT9557 adds the output waveforms from the high accuracy sensors connected to each branch line of the multi-cable wiring, for the highly accurate measurement of large currents.



Extensive Interface for Linking with External Devices

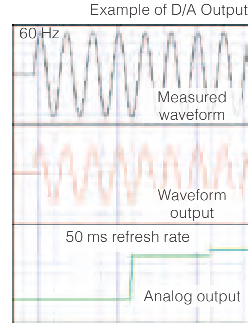
Wide variety of built-in interfaces, including LAN, USB (communication, memory), CF cards, RS-232C, synchronization control, and external control.
D/A output* delivers analog output at 50 ms for up to 16 parameters. The voltage and current waveform** for each channel can also be output.

Interface unit



D/A output terminal

Example of D/A Output



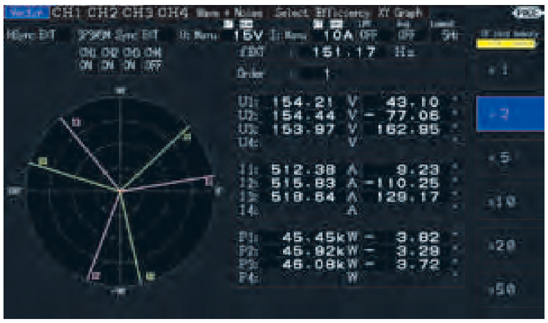
* Built-in for PW3390-02 and PW3390-03
** During waveform output, accurate reproduction is possible at an output of 500 kS/s and with a sine wave up to 20 kHz.

Switch Screens with a Single Touch, Accessing a Variety of Power Analysis Methods

The power analysis engine allows the simultaneous, parallel calculation of all parameters. Access a variety of analysis methods simply by pressing the page keys to switch screens.

Page Keys

Vector

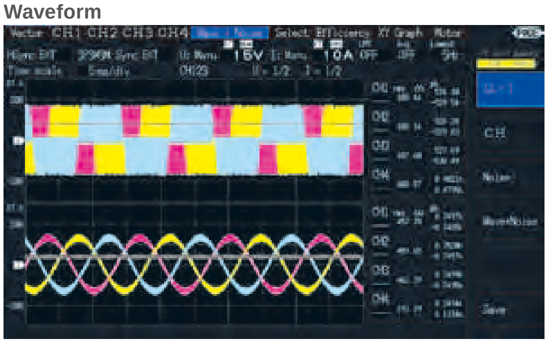


Confirm the voltage/current/power/phase angle for each harmonic order on a vector graph and as numerical values.

Selection Display

Select 4/8/16/32 display parameters individually for each screen, and summarize them on a single screen.

Waveform

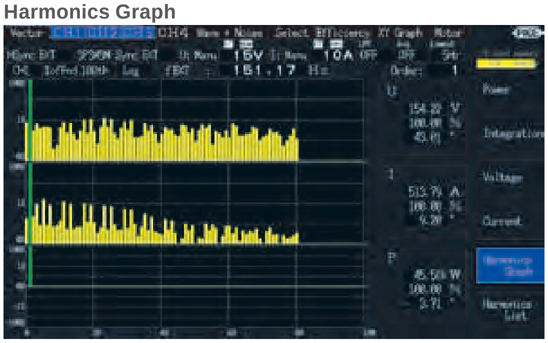


Display voltage/current waveforms for 4 channels at a high speed of 500 kS/s or a maximum length of 5 seconds. Waveform data can be saved.

Noise

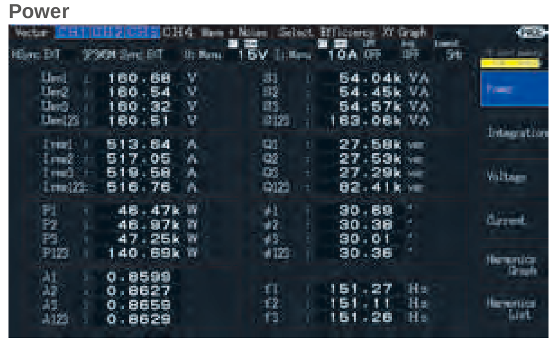
Display FFT results for voltage and current as graphs and numerical values, up to a maximum of 100 kHz. This is perfect for the frequency analysis of inverter noise.

Harmonics Graph



Display harmonics up to the 100th order for voltage/current/power in bar graphs. Confirm the numerical data for the selected order at the same time.

Power

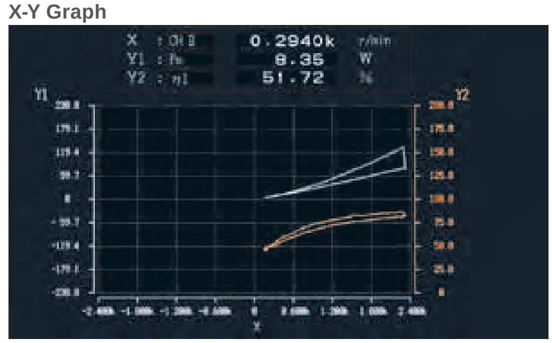


On the basic measurement screen, display voltage/current/power/power factor/frequency and other parameters in a list for each connection.

Efficiency and Loss

Using active power values and motor power values, confirm efficiency η [%] and loss [W] and total efficiency for each inverter/motor on a single unit at the same time.

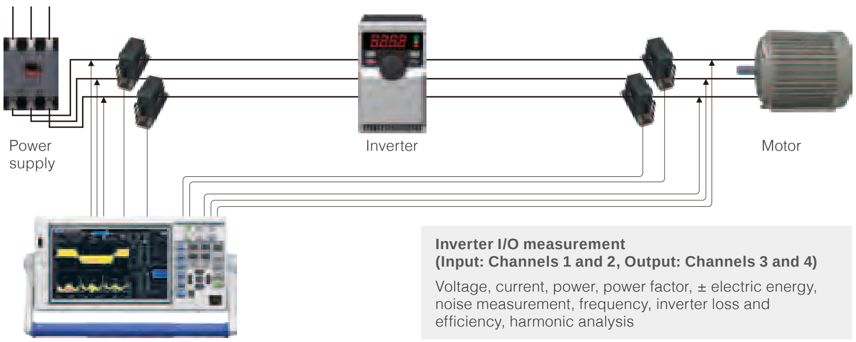
X-Y Graph



Create inverter characteristic evaluations and motor torque maps. Select the desired parameter to display an X-Y plot graph.

Applications

Measure the Power Conversion Efficiency of Inverters

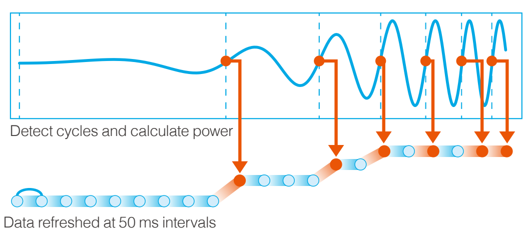


Key features

1. Isolated input of voltage and current on each of 4 channels for simultaneous measurement of the primary and secondary power of inverters
2. Simultaneous measurement of all important parameters for secondary analysis of inverters, such as RMS value, MEAN value, and fundamental components
3. Easy wiring with current sensors. Reliable confirmation of wiring with vector diagrams
4. Current sensors reduce effects of common mode noise from inverters during power measurement
5. Simultaneous measurement of noise components, in addition to the harmonic analysis required for the measurement of inverter control

Highly Accurate and Fast 50 ms Calculation of Power in Transient State

Measure power transient states, including motor operations such as starting and accelerating, at 50 ms refresh rates. Automatically measure and keep up with power with fluctuating frequencies, from a minimum of 0.5 Hz.

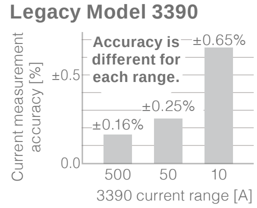


Automatic detection of fundamental wave even if the frequency fluctuates, from low to high frequencies

Combined Accuracy of Current Sensors Applicable throughout Entire Range

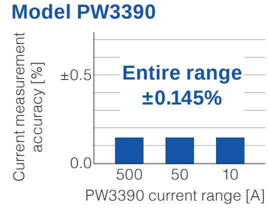
Combined accuracy throughout the entire range is provided through the use of a built-to-order high accuracy pass-through type current sensor. Obtain highly accurate measurements regardless of range, from large to minute currents, even for loads that fluctuate greatly.

Legacy Model 3390



Combination of 3390 and 9709 (500 A rating)
Total Accuracy when measuring currency of 45 to 66 Hz and f.s. for each range

Model PW3390

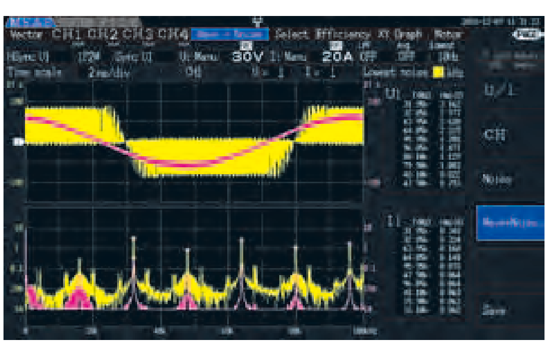


Combination of PW3390 and the high accuracy 9709-05* (500 A rating, built-to-order)
Total accuracy when measuring currency of 45 to 66 Hz and f.s. for each range

* High-accuracy specifications are not defined for the built-to-order high accuracy current sensor when used alone.

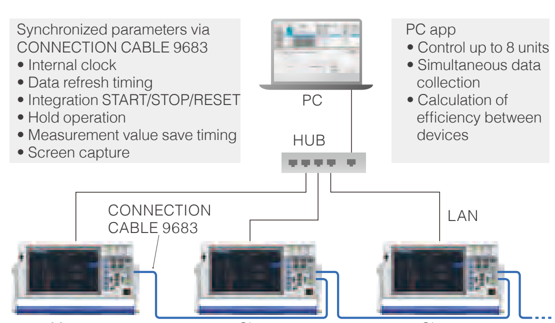
Measure High-Frequency Noise in Inverters

Power supply problems caused by high switching inverter frequencies are unrelated to the fundamental frequency, making it difficult to conduct proper harmonic analysis. The noise analysis function performs a frequency analysis of noise components up to 100 kHz, and displays the frequency, and voltage and current levels for the top 10 points. This is effective for measuring high-frequency noise in inverters.

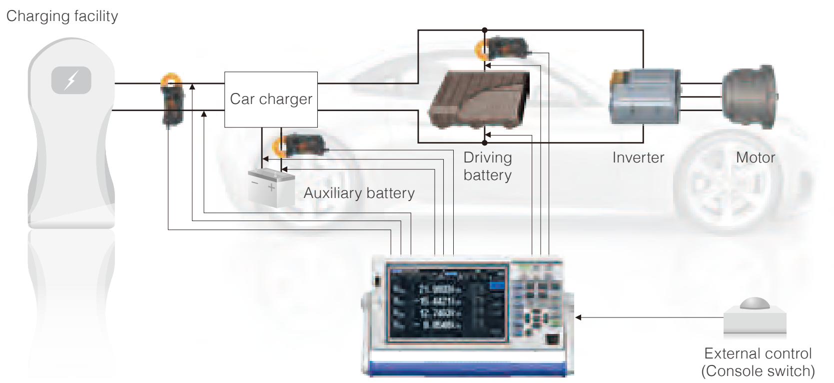


Acquire Data from up to 8 Synchronized Units (32 Channels)

When you connect CONNECTION CABLE 9683 to multiple PW3390 units, the control signals and internal clocks synchronize. From the master unit, you can control the measurement timing on the PW3390 units that are set as slaves. With interval measurement, you can save synchronized measurement data to a CF card or a PC to achieve simultaneous measurements across a larger number of systems.



Test Automobile Fuel Economy

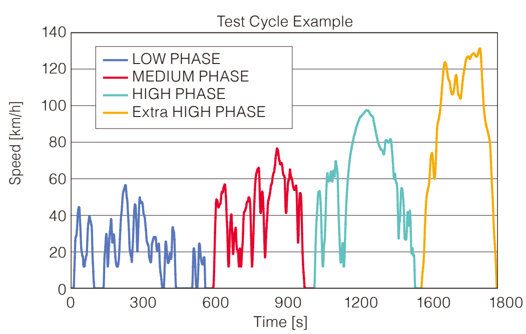


Key features

1. Accurately measure recharge and discharge power with excellent basic accuracy and DC accuracy.
2. 4 built-in channels, standard. Support for multiple recharge and discharge measurements, including auxiliary batteries.
3. Easily achieve highly accurate measurements with clamp sensors, which can be used in a wide range of operating temperatures.
4. Easily link with other measuring instruments through integration control with an external control interface.

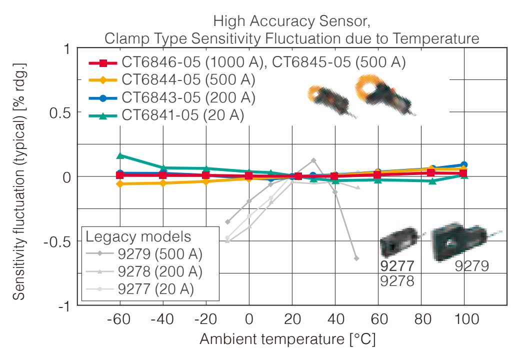
Evaluate WLTP Mode Performance - A New Fuel Economy Standard

Taking fuel economy measurements that comply with WLTP standards requires the precise measurement of current integration and power integration for the recharging/discharging of each battery in the system. High accuracy clamp current sensors, the excellent DC accuracy of the PW3390, and the ability to integrate current and power at 50 ms intervals are extremely effective in meeting this application.



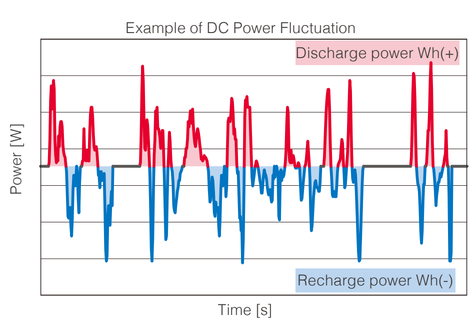
Optimal Current Sensors for Automotive Testing

Easily connect high accuracy clamp-type sensors without cutting the cables. Sensors operate over a temperature range of -40°C to 85°C (-40°F to 185°F), characteristics that enable highly accurate measurements even inside the engine room of a car.



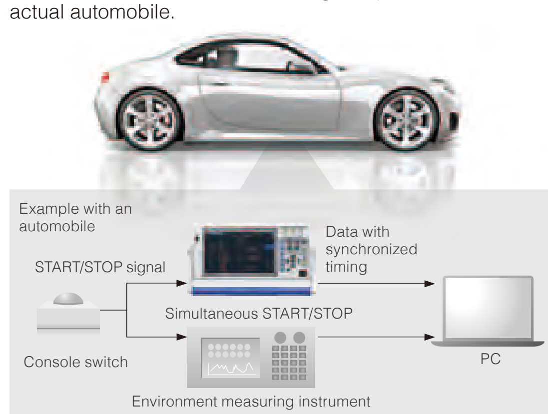
Current and Power Integration Function by Polarity

DC integration measurement integrates the recharging power and discharging power by polarity for every sample at 500 kS/s, and measures positive-direction power magnitude, negative-direction power magnitude, and the sum of positive- and negative-direction power magnitude during the integration period. Accurate measurement of recharging power and discharging power is possible even if there is rapid repetition of battery recharging/discharging.



Link to Peripheral Devices via External Control

Use external control terminals to START/STOP integration and capture screen shots. This makes it easy to control operations from console switches and link to the timing of other instruments when measuring the performance of an actual automobile.



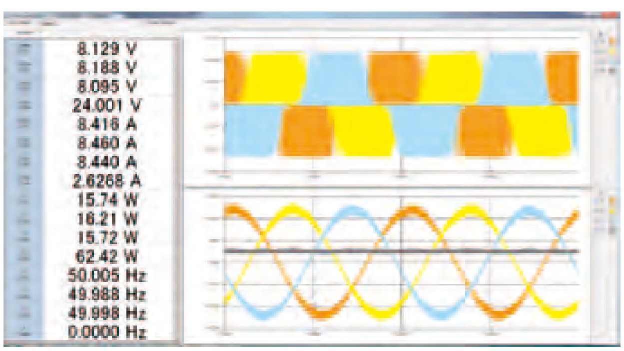
External Appearance

Software

Download software, drivers, and the Communications Command Instruction Manual from the Hioki website. https://www.hioki.com

"PW Communicator" PC Communication Software (Available soon)

PW Communicator is an application program for communicating between a PW3390 series power analyzer and a PC. It includes many useful functions, such as configuring PW3390 settings, monitoring measurement values, saving CSV data, and calculating efficiency.



Numerical value monitoring	Display the PW3390's measurement values on the PC screen. You can freely select up to 32 values, such as voltage, current, power, and harmonics.
Waveform monitoring	Monitor the measured voltage, current, and waveforms on the PC screen.
Meter setting	Change the settings of the connected PW3390 from the PC screen.
Measure with multiple units	In addition to the PW3390, it is also possible to perform batch control of up to 8 devices from the HIOKI PW6001 Power Analyzer and the PW3335, PW3336, and PW3337 Power Meter series. You can also simultaneously record measured data to the PC, and perform efficiency calculations for measuring instruments.
Record in CSV format	Record measured data to a CSV file at regular time intervals. The minimum recording interval is 50 ms.

Operating environment	PC/AT-compatible computer
OS	Windows 10 Windows 8 Windows 7 (32bit/64bit) * Windows is a registered trademark of Microsoft Corporation in the United States and/or other countries.
Memory	2 GB or more recommended
Interface	LAN/RS-232C/USB

LabVIEW Driver (Available soon)

Obtain data and configure measurement systems with the LabVIEW driver.

* LabVIEW is a registered trademark of NATIONAL INSTRUMENTS.

Specifications

Basic Specifications

Accuracy guaranteed for 6 months (and 1.25 times specified accuracy for one year)
Post-adjustment accuracy guaranteed for: 6 months

-1. Power Measurement Input Specifications

Measurement line type	Single-phase 2-wire (1P2W), Single-phase 3-wire (1P3W), 3-phase 3-wire (3P3W2M, 3P3W3M), 3-phase 4-wire (3P4W)

	CH1	CH2	CH3	CH4
Pattern 1	1P2W	1P2W	1P2W	1P2W
Pattern 2	1P3W		1P2W	1P2W
Pattern 3	3P3W2M		1P2W	1P2W
Pattern 4	1P3W		1P3W	
Pattern 5	3P3W2M		1P3W	
Pattern 6	3P3W2M		3P3W2M	
Pattern 7	3P3W3M			1P2W
Pattern 8	3P4W			1P2W

Number of input channels	Voltage: 4 channels U1 to U4 Current: 4 channels I1 to I4
Measurement input terminal type	Voltage: Plug-in jacks (safety jacks) Current: Dedicated custom connectors (ME15W)
Input methods	Voltage: Isolated inputs, resistive dividers Current: Insulated current sensors (voltage output)
Voltage range	15 V/30 V/60 V/150 V/300 V/600 V/1500 V (Selectable for each measured wiring system. AUTO range available.)
Current range ( ): Sensor used	2 A/4 A/8 A/20 A (with the 9272-05, 20 A) 0.4 A/0.8 A/2 A/4 A/8 A/20 A (with the CT6841-05) 4 A/8 A/20 A/40 A/80 A/200 A (200 A sensor) 40 A/80 A/200 A/400 A/800 A/2 kA (2000 A sensor) 0.1 A/0.2 A/0.5 A/1 A/2 A/5 A (5 A sensor) 1 A/2 A/5 A/10 A/20 A/50 A (50 A sensor) 10 A/20 A/50 A/100 A/200 A/500 A (500 A sensor) 20 A/40 A/100 A/200 A/400 A/1 kA (1000 A sensor) 400 A/800 A/2 kA (CT7642 and CT7742) 400 A/800 A/2 kA/4 kA/8 kA (CT7044, CT7045, and CT7046) 400 A/800 A/2 kA/4 kA/8 kA/20 kA (100 uV/A sensor) 40 A/80 A/200 A/400 A/800 A/2 kA (1 mV/A sensor) 4 A/8 A/20 A/40 A/80 A/200 A (10 mV/A sensor) 0.4 A/0.8 A/2 A/4 A/8 A/20 A (100 mV/A sensor) (Selectable for each measured wiring system. AUTO range available.)
Power range	Determined automatically by the combination of voltage range, current range, and measurement line. 1.5000 W to 90.00 MW
Crest factor	300 (relative to minimum effective voltage/current input) (for 1500 V range: 133) 3 (relative to voltage/current range rating) (for 1500 V range: 1.33)
Input resistance (50 Hz/60 Hz)	Voltage input section : 2 MΩ ±40 kΩ (differential input and insulated input) Current sensor input section : 1 MΩ ±50 kΩ
Maximum input voltage	Voltage input section : 1500 V, ±2000 Vpeak Current sensor input section : 5 V, ±10 Vpeak
Maximum rated voltage to earth	Voltage input terminal 1000 V (50 Hz/60 Hz) Measurement categories III 600 V (anticipated transient overvoltage 6000 V) Measurement categories II 1000 V (anticipated transient overvoltage 6000 V)
Measurement method	Simultaneous digital sampling of voltage and current, simultaneous zero-crossing calculation method
Sampling	500 kHz/16 bit
Measurement frequency range	DC, 0.5 Hz to 200 kHz
Synchronization frequency range	0.5 Hz to 5 kHz Selectable lower limit measurement frequency (0.5 Hz/1 Hz/2 Hz/5 Hz/10 Hz/20 Hz)
Synchronization source	U1 to U4, I1 to I4, Ext (with the motor evaluation installed model and CH B set for pulse input), DC (50 ms or 100 ms fixed) Selectable for each measurement channel (U/I for each channel measured using the same synchronization source) The zero-crossing filter automatically matches the digital LPF when U or I is selected. Two filter levels (strong or mild) Operation and accuracy are undetermined when the zero-crossing filter is disabled (off). Operation and accuracy are determined when U or I is selected and measured input is 30% f.s. or above.
Data update interval	50 ms
LPF	OFF/500 Hz/5 kHz/100 kHz (selectable for each wiring system) 500 Hz: Accuracy defined at 60 Hz or below (Add ±0.1% f.s.) 5 kHz: Accuracy defined at 500 Hz or below 100 kHz: Accuracy defined at 20 kHz or below (Add 1% rdg. at or above 10 kHz)
Zero-crossing filter	Off, mild or strong
Polarity discrimination	Voltage/current zero-crossing timing comparison method Zero-crossing filter provided by digital LPF
Basic measurement parameters	Frequency, RMS voltage, voltage mean value rectification RMS equivalent, voltage AC component, voltage simple average, voltage fundamental wave component, voltage waveform peak +, voltage waveform peak -, voltage total harmonic distortion, voltage ripple factor, voltage unbalance factor, RMS current, current mean value rectification RMS equivalent, current AC component, current simple average, current fundamental wave component, current waveform peak +, current waveform peak -, current total harmonic distortion, current ripple factor, current unbalance factor, active power, apparent power, reactive power, power factor, voltage phase angle current phase angle, power phase angle, positive-direction current magnitude, negative-direction current magnitude, sum of positive- and negative-direction current magnitude, positive-direction power magnitude, negative-direction power magnitude, sum of positive- and negative-direction power magnitude, efficiency, loss (PW3390-03) Motor torque, rpm, motor power, slip
Voltage/current rectification method	Select which voltage and current values to use for calculating apparent and reactive power, and power factor RMS/MEAN (voltage and current in each phase system)
Display resolution	99,999 counts (other than the integrated value) 999,999 counts (Integrated value)

Accuracy

	Voltage (U)	Current (I)
DC	±0.05% rdg. ±0.07% f.s.	±0.05% rdg. ±0.07% f.s.
0.5 Hz ≤ f < 30 Hz	±0.05% rdg. ±0.1% f.s.	±0.05% rdg. ±0.1% f.s.
30 Hz ≤ f < 45 Hz	±0.05% rdg. ±0.1% f.s.	±0.05% rdg. ±0.1% f.s.
45 Hz ≤ f ≤ 66 Hz	±0.04% rdg. ±0.05% f.s.	±0.04% rdg. ±0.05% f.s.
66 Hz < f ≤ 1 kHz	±0.1% rdg. ±0.1% f.s.	±0.1% rdg. ±0.1% f.s.
1 kHz < f ≤ 10 kHz	±0.2% rdg. ±0.1% f.s.	±0.2% rdg. ±0.1% f.s.
10 kHz < f ≤ 50 kHz	±0.3% rdg. ±0.2% f.s.	±0.3% rdg. ±0.2% f.s.
50 kHz < f ≤ 100 kHz	±1.0% rdg. ±0.3% f.s.	±1.0% rdg. ±0.3% f.s.
100 kHz < f ≤ 200 kHz	±20% f.s.	±20% f.s.

	Active power (P)	Phase difference
DC	±0.05% rdg. ±0.07% f.s.	-
0.5 Hz ≤ f < 30 Hz	±0.05% rdg. ±0.1% f.s.	±0.08°
30 Hz ≤ f < 45 Hz	±0.05% rdg. ±0.1% f.s.	±0.08°
45 Hz ≤ f ≤ 66 Hz	±0.04% rdg. ±0.05% f.s.	±0.08°
66 Hz < f ≤ 1 kHz	±0.1% rdg. ±0.1% f.s.	±0.08°
1 kHz < f ≤ 10 kHz	±0.2% rdg. ±0.1% f.s.	±(0.06*f+0.02)°
10 kHz < f ≤ 50 kHz	±0.4% rdg. ±0.3% f.s.	±0.62°
50 kHz < f ≤ 100 kHz	±1.5% rdg. ±0.5% f.s.	±(0.005*f+0.4)°
100 kHz < f ≤ 200 kHz	±20% f.s.	±(0.022*f-1.3)°

Values of f in above tables are given in kHz.
Accuracy figures for DC voltage and current are defined for Udc and Idc, while accuracy figures for frequencies other than DC are defined for Urms and Irms.
Accuracy figures for phase difference values are defined for full-scale input with a power factor of zero and the LPF disabled.
Accuracy figures for voltage, current, and active power values in the frequency range of 0.5 Hz to 10 Hz are provided as reference values.
Accuracy figures for voltage and active power values in excess of 220 V in the frequency range of 10 Hz to 16 Hz are provided as reference values.
Accuracy figures for voltage and active power values in excess of 750 V in the frequency range of 30 kHz to 100 kHz are provided as reference values.
Accuracy figures for voltage and active power values in excess of (22,000/f [kHz]) V in the frequency range of 100 kHz to 200 kHz are provided as reference values.
Accuracy figures for voltage and active power values in excess of 1000 V are provided as reference values.
Accuracy figures for phase difference values outside the frequency range of 45 Hz to 66 Hz are provided as reference values.
For voltages in excess of 600 V, add the following to the phase difference accuracy:
500 Hz < f ≤ 5 kHz:±0.3°
5 kHz < f ≤ 20 kHz:±0.5°
20 kHz < f ≤ 200 kHz:±1°
Add ±20 µV to the DC current and active power accuracy (at 2 V f.s.)

Add the current sensor accuracy to the above accuracy figures for current, active power, and phase difference.
However, the combined accuracy is defined separately for the current measurement options listed below.

When used with current measurement options PW9100-03 or PW9100-04, combined accuracy is defined as follows (with PW3390 range as f.s.):

	Current (I)	Active power (P)
DC	±0.07% rdg. ±0.077% f.s.	±0.07% rdg. ±0.077% f.s.
45 Hz ≤ f ≤ 66 Hz	±0.06% rdg. ±0.055% f.s.	±0.06% rdg. ±0.055% f.s.

Add ±0.12% f.s. (f.s. = PW3390 range) when using 1 A or 2 A range.

When used with any of the following current measurement options: special-order high-accuracy 9709-05, high-accuracy CT6862-05, or high-accuracy CT6863-05, combined accuracy is defined as follows (with PW3390 range as f.s.):

	Current (I)	Active power (P)
DC	±0.095% rdg. ±0.08% f.s.	±0.095% rdg. ±0.08% f.s.
45 Hz ≤ f ≤ 66 Hz	±0.085% rdg. ±0.06% f.s.	±0.085% rdg. ±0.06% f.s.

Apply LPF accuracy definitions to the above accuracy figures when using the LPF.

Conditions of guaranteed accuracy	Temperature and humidity for guaranteed accuracy: 23°C ±3°C (73°F ±5°F), 80% R.H. or less Warm-up time: 30 min. or more Input: Within the specified ranges when the fundamental wave is synchronized with the sync source, for sine wave input, power factor of one, or DC input, zero ground voltage, within effective measurement range after zero-adjustment and within the range in which the fundamental wave satisfies the synchronization source conditions
Temperature coefficient	±0.01% f.s./°C (for DC, add ±0.01% f.s./°C)
Effect of common mode voltage	±0.01% f.s. or less (with 1000 V @50 Hz/60 Hz applied between voltage measurement jacks and chassis)
Magnetic field interference	±1% f.s. or less (in 400 A/m magnetic field, DC and 50 Hz/60 Hz)
Power factor influence	Other than φ = ±90°: ±(1-cos (φ+Phase difference accuracy)/cos(φ)) ×100% rdg. When φ = ±90°: ±cos (φ+Phase difference accuracy) ×100% f.s.
Susceptibility to conducted electromagnetic field	@3 V, current and active power not more than ±6% f.s., where f.s. current is the rated primary-side current of the current sensor f.s. active power equals the voltage range × the rated primary-side current of the current sensor
Susceptibility to radiated electromagnetic field	@10 V/m, current and active power not more than ±6% f.s., where f.s. current is the rated primary-side current of the current sensor f.s. active power equals the voltage range × the rated primary-side current of the current sensor
Effective measuring range	Voltage, Current, Power: 1% to 110% of the range
Total display area	Voltage, Current, Power: from zero-suppression range setting to 120%
Zero-suppression ranges	Selectable OFF, 0.1 or 0.5% f.s. When OFF, non-zero values may be displayed even with no measurement input
Zero adjustment	Voltage: Zero-adjustment compensation of internal offset at or below ±10% f.s. Current: Zero-adjustment compensation of input offset at or below ±10% f.s. ±4 mV
Waveform peak measurement range	Within ±300% of each voltage and current range
Waveform peak measurement accuracy	Within ±2% f.s. of voltage and current display accuracy

-2. Frequency Measurement Specifications

Measurement channels	Four (f1 to f4)
Measurement source	Select U/I for each measurement channel
Measurement method	Reciprocal method + zero-crossing sample value correction
Measuring range	Synchronous range from 0.5 Hz to 5 kHz (with "0.0000 Hz" or "----- Hz" unmeasurable time)
Lower limit measurement frequency	0.5 Hz/1 Hz/2 Hz/5 Hz/10 Hz/20 Hz
Data update interval	50 ms (measurement-frequency-dependent at 45 Hz and below)
Accuracy	±0.01 Hz (during voltage frequency measurement within the range of 45 Hz to 66 Hz) ±0.05% rdg., ±1 dgt. (under other conditions) With sine wave of at least 30% of the measurement source's measurement range
Numerical display format	0.5000 Hz to 9.9999 Hz, 9.900 Hz to 99.999 Hz, 99.00 Hz to 999.99 Hz, 0.9900 kHz to 5.0000 kHz

-3. Integration Measurement Specifications

Measurement mode	Selectable between RMS or DC for each wiring mode
Measurement items	Current integration (Ih+, Ih-, and Ih), active power integration (WP+, WP-, and WP) Ih+ and Ih- only for DC mode measurements, and Ih only for RMS mode measurements
Measurement method	Digital calculation from each current and active power phase (when averaging, calculates with previous average value) In DC mode: calculates current value at every sample, and integrates instantaneous power independent of polarity In RMS mode: Integrates current effective values between measurement intervals, and polarity-independent active power value
Measurement interval	50 ms data update interval
Measuring range	Integration value: 0 Ah/Wh to ±9999.99 TAh/TWh Integration time: No greater than 9999h59m
Integration time accuracy	±50 ppm ±1 dgt. (0°C to 40°C (32°F to 104°F))
Integration accuracy	± (current and active power accuracy) ± integration time accuracy
Backup function	Integration automatically resumes after power outages.

-4. Harmonic Measurement Specifications

Number of measurement channels	4 channels Harmonic measurements not available for multiple systems with different frequencies.
Measurement items	Harmonic rms voltage, harmonic voltage percentage, harmonic voltage phase angle, harmonic rms current, harmonic current percentage, harmonic current phase angle, harmonic active power, harmonic power percentage, harmonic voltage-current phase difference, total harmonic voltage distortion, total harmonic current distortion, voltage unbalance factor, current unbalance factor
Measurement method	Zero-crossing synchronous calculation (all channels in same window), with gap Fixed 500 kS/s sampling, after digital anti-aliasing filter Equal thinning between zero crossings (with interpolation calculation)
Harmonic sync source	U1 to U4, I1 to I4, External (with motor analysis and CH B set for pulse input), DC selectable (50 ms or 100 ms)
FFT calculation word length	32 bits
Anti-aliasing filter	Digital filter (automatically set based on synchronization frequency)
Windows	Rectangular
Synchronization frequency range	As specified for power measurements
Data update interval	50 ms (measurement-frequency-dependent at 45 Hz and below)
Phase zero adjustment	Provided by key operation or external control command (only with external sync source)
THD calculation	THD-F/THD-R

Highest order analysis and window waveforms

Synchronization frequency range	Window waveforms	Analysis order
0.5 Hz ≤ f < 40 Hz	1	100th
40 Hz ≤ f < 80 Hz	1	100th
80 Hz ≤ f < 160 Hz	2	80th
160 Hz ≤ f < 320 Hz	4	40th
320 Hz ≤ f < 640 Hz	8	20th
640 Hz ≤ f < 1.2 kHz	16	10th
1.2 kHz ≤ f < 2.5 kHz	32	5th
2.5 kHz ≤ f < 5.0 kHz	64	3th

Accuracy

Frequency	Voltage(U), Current(I), Active Power(P)
0.5 Hz ≤ f < 30 Hz	±0.4% rdg. ±0.2% f.s.
30 Hz ≤ f ≤ 400 Hz	±0.3% rdg. ±0.1% f.s.
400 Hz < f ≤ 1 kHz	±0.4% rdg. ±0.2% f.s.
1 kHz < f ≤ 5 kHz	±1.0% rdg. ±0.5% f.s.
5 kHz < f ≤ 10 kHz	±2.0% rdg. ±1.0% f.s.
10 kHz < f ≤ 13 kHz	±5.0% rdg. ±1.0% f.s.

Not specified for sync frequencies of 4.3 kHz and higher
Add the LPF accuracy to the above when using LPF.

-5. Noise Measurement Specifications

Calculation channels	1 (Select one from CH1 to CH4)
Calculation items	Voltage noise/Current noise
Calculation type	RMS spectrum
Calculation method	Fixed 500 kS/s sampling, thinning after digital anti-aliasing filter
FFT calculation word length	32 bits
FFT data points	1000/5000/10,000/50,000 (according to displayed waveform recording length)
Anti-aliasing filter	Automatic digital filter (varies with maximum analysis frequency)
Windows	Rectangular/Hanning/flat-top
Data update interval	Determined by FFT points within approx. 400 ms, 1 s, 2 s, or 15 s, with gap
Highest analysis frequency	100 kHz/50 kHz/20 kHz/10 kHz/5 kHz/2 kHz
Frequency resolution	0.2 Hz to 500 Hz (Determined by FFT points and maximum analysis frequency)
Noise amplitude measurement	Calculates the ten highest level and frequency voltage and current FFT peak values (local maxima).
Lower limit noise frequency	0 kHz to 10 kHz

-6. Motor Analysis Specifications (Model PW3390-03)

Number of input channels	3 channels CH A: Analog DC input/Frequency input (selectable) CH B: Analog DC input/Pulse input (selectable) CH Z: Pulse input
Measurement input terminal type	Insulated BNC jacks
Input impedance (DC)	1 MΩ ±100 kΩ
Input methods	Isolated and differential inputs (not isolated between channels B and Z)
Measurement items	Voltage, torque, rotation rate, frequency, slip, and motor power
Synchronization source	U1 to U4, I1 to I4, Ext (with CH B set for pulse input), DC (50 ms/100 ms) Common to channels A and B
Measurement frequency source	f1 to f4 (for slip calculations)
Maximum input voltage	±20 V (during analog, frequency, and pulse input)
Maximum rated voltage to earth	50 V (50 Hz/60 Hz)

(1). Analog DC Input (CH A/CH B)

Measurement range	±1 V, ±5 V, ±10 V (when inputting analog DC)
Valid input range	1% to 110% f.s.
Sampling	10 kHz/16 bits
Response time	1 ms (measuring zero to full scale, with LPF off)
Measurement method	Simultaneous digital sampling and zero-crossing synchronous calculation system (cumulative average of intervals between zero crossings)
Measurement accuracy	±0.08% rdg. ±0.1% f.s.
Temperature coefficient	±0.03% f.s./°C
Effect of common mode voltage	Not more than ±0.01% f.s. (with 50 V [DC or 50 Hz/60 Hz] between measurement jacks and PW3390 chassis)
Effect of external magnetic field	Not more than ±0.1% f.s. (at 400 A/m DC and 50 Hz/60 Hz magnetic fields)
LPF	OFF/ON (OFF: 4 kHz, ON: 1 kHz)
Total display area	Zero-suppression range setting ±120%
Zero adjustment	Zero-corrected input offset of voltage ±10% f.s. or less
Scaling	0.01 ~ 9999.99
Unit	CH A: V, N• m, mN• m, kN• m CH B: V, Hz, r/min

(2). Frequency Input (CH A only)

Valid amplitude range	±5 V peak (5 V symmetrical, equivalent to RS-422 complementary signal)
Max. measurement frequency	100 kHz
Measurement range	1 kHz to 100 kHz
Data output interval	According to synchronization source
Measurement accuracy	±0.05% rdg., ±3 dgt.
Total display area	1.000 kHz to 99.999 kHz
Frequency range	Select fc and fd for frequency range fc ± fd [Hz] (frequency measurement only) 1 kHz to 98 kHz in 1 kHz units, where fc + fd < 100 kHz and fc – fd > 1 kHz
Rated torque	1 ~ 999
Unit	Hz, N• m, mN• m, kN• m

(3). Pulse Input (CH B only)

Detection level	Low: 0.5 V or less; High: 2.0 V or more
Measurement range	1 Hz to 200 kHz (at 50% duty)
Division setting range	1 ~ 60000
Measurement frequency range	0.5 Hz to 5.0 kHz (limited to measured pulse frequency divided by selected no. of divisions)
Minimum detectable pulse width	2.5 µs or more
Measurement accuracy	±0.05% rdg., ±3 dgt.
Motor poles	2 ~ 98
Max. measurement frequency	100 Hz, 500 Hz, 1 kHz, 5 kHz
Pulse count	Integer multiple of half the number of motor poles, from 1 to 60,000
Unit	Hz, r/min

(4). Pulse Input (CH Z only)

Detection level	Low: 0.5 V or less; High: 2.0 V or more
Measurement range	0.1 Hz to 200 kHz (at 50% duty)
Minimum detectable pulse width	2.5 µs or more
Settings	OFF/Z Phase/B Phase (clear counts of CHB in rising edge during Z Phase, detect polar code for number of rotations during B Phase)

-7. D/A Output Option Specifications (Models PW3390-02 and PW3390-03)

Number of output channels	16 channels
Output contents	CH1 to CH8: Selectable analog/waveform outputs CH9 to CH16: Analog output
Output items	Analog output: Select a basic measurement item for each output channel. Waveform output: Output voltage or current measured waveforms.
Output connector	One 25-pin female D-sub
D/A conversion resolution	16 bits (polarity + 15 bits)
Output accuracy	Analog output: Measurement accuracy ±0.2% f.s. (DC level) Waveform output: Measurement accuracy ±0.5% f.s. (at ±2 V f.s.), ±1.0% f.s. (at ±1 V f.s.) (rms level within synchronous frequency range)
Output update interval	Analog output: 50 ms (according to input data update interval of selected parameter) Waveform output: 500 kHz
Output voltage	Analog output: ±5 V DC nom. (approx. ±12 V DC max.) Waveform output: ±2 V/±1 V switchable, crest factor of 2.5 or greater Setting applies to all channels.
Output impedance	100 Ω ±5 Ω
Temperature coefficient	±0.05% f.s./°C

-8. Display Specifications

Display type	9-inch TFT color LCD (800×480 dots)
Display refresh interval	Measurement values: 200 ms (independent of internal data update interval) Waveforms, FFT: screen-dependent

-9. External Interface Specifications

(1). USB Interface (Functions)

Connector	Mini-B receptacle ×1
Compliance standard	USB2.0 (Full Speed/High Speed)
Class	Individual (USB488h)
Connection destination	Computer (Windows10/Windows8/Windows7, 32bit/64bit)
Function	Data transfer and command control

(2). USB Memory Interface

Connector	USB type A connector ×1
Compliance standard	USB2.0
USB power supply	500 mA maximum
USB storage device support	USB Mass Storage Class
Function	Save and load settings files, Save waveform data Save displayed measurement values (CSV format) Copy measurement values and recorded data (from CF card) Save screen captures

(3). LAN Interface

Connector	RJ-45 connector × 1
Compliance standard	IEEE 802.3 compliant
Transmission method	10BASE-T/100BASE-TX Auto detected
Protocol	TCP/IP
Function	HTTP server (remote operation), Dedicated port (data transfer and command control)

(4). CF Card Interface

Slot	One Type 1
Compatible card	CompactFlash memory card (32 MB or higher)
Supported memory capacity	Up to 2 GB
Data format	MS-DOS format (FAT16/FAT32)
Recordable content	Save and load settings files, Save waveform data Save displayed measurement values and auto-recorded data (CSV format) Copy measurements/recorded data (from USB storage) Save screen captures

(5). RS-232C Interface

Method	RS-232C, [EIA RS-232D], [CCITT V.24], [JIS X5101] compliant Full duplex, start-stop synchronization, 8-bit data, no parity, one stop bit Hardware flow control, CR+LF delimiter
Connector	D-sub9 pin connector ×1
Communication speeds	9600 bps, 19,200 bps, 38,400 bps
Function	Command control, Bluetooth® logger connectivity (simultaneous use not supported)

(6). Synchronization Control Interface

Signal contents	One-second clock, integration START/STOP, DATA RESET, EVENT
Connector types	IN: One 9-pin female mini-DIN jack, OUT: One 8-pin female mini-DIN jack
Signal	5 V CMOS
Max. input	±20 V
Max. signal delay	2 µs (rising edge)

(7). External Control Interface

Connector types	9-pin round connector ×1; also used as synchronization control interface
Electrical specifications	Logic signal of 0 V/5 V (2.5 V to 5 V), or contact signal (shorted/open)
Function	Integration start, integration stop, data reset, event (the event set as the synchronization control function) Cannot be used at the same time as synchronization control.

Function Specifications

-1. Control Functions

AUTO range function	Automatically selects voltage and current ranges according to measured amplitude on each phase. Operating states: Selectable on or off for each phase system Auto-ranging span: Wide/Narrow (common to all wiring systems)
Timing control function	Interval OFF/50 ms/100 ms/200 ms/500 ms/1 s/5 s/10 s/ 15 s/30 s/1 min/5 min/10 min/15 min/30 min/60 min Setting determines the maximum data-saving capacity Timing controls OFF/Timer/RTC Timer : 10 s to 9999:59:59 [h:m:s] (in seconds) Real-time clock : Start and stop times (in minutes)
Hold function	Stops all updating of displayed measurement values and waveforms, and holds display. Internal calculations such as integration and averaging, clock, and peak-over display continue to be updated.
Peak hold function	All measurement values are updated to display the maximum value for each measurement. Displayed waveforms and integration values continue to be updated with instantaneous values.

-2. Calculation Functions

Scaling calculation	VT(PT) ratio and CT ratio: OFF/0.01 to 9999.99
Average calculation	OFF/FAST/MID/SLOW/SLOW2/SLOW3 Exponentially averages all instantaneous measurement values including harmonics (but not peak, integration, or FFT noise values). Applied to displayed values and saved data. Response speed (time remains within specified accuracy when input changes from 0 to 100% f.s.) FAST: 0.2 s, MID: 1.0 s, SLOW: 5 s, SLOW2: 25 s, SLOW3: 100 s
Efficiency and loss calculations	Efficiency η [%] and Loss [W] are calculated from active power values measured on each phase and system. For PW3390-03, motor power (Pm) is also applied as a calculation item. Maximum no. of simultaneous calculations: Efficiency and loss, by three formulas (Parameters are specified for Pin and Pout) Calculation method: Efficiency η = 100 × ǀPoutǀ/ǀPinǀ Loss = ǀPinǀ - ǀPoutǀ
Δ-Y calculation	For 3P3W3M systems, converts between line-to-line voltage and phase voltage waveforms using a virtual center point. All voltage parameters including harmonics such as true rms voltage are calculated as phase voltage waveforms. U1s = (U1s-U3s)/3, U2s = (U2s-U1s)/3, U3s =(U3s-U2s)/3
Selecting the calculation method	TYPE1/TYPE2 (only valid when wiring is 3P3W3M) Select the calculation method used to calculate the apparent power and reactive power during 3P3W3M wiring. Only affect measurement values S123, Q123, φ123, λ123
Current sensor phase correction calculations	Compensation by calculating the current sensor's harmonic phase characteristics Correction points are set using frequency and phase difference (set separately for each wiring mode). Frequency: 0.001 kHz to 999.999 kHz (in 0.001 kHz increments) Phase difference: 0.00 deg. to ±90.00 deg. (in 0.01 deg. increments) However, the time difference calculated from the frequency phase difference is limited to a maximum of 200 us in 5 ns increments.

-3. Display Functions

Wiring Check screen	The wiring diagram and voltage/current vectors are displayed for the selected wiring system(s). The correct range for the wiring system is shown on the vector display, to confirm proper measurement cable connections.
Independent wiring system display mode	Displays power and harmonic measurement values for channels 1 to 4. A composite measurement line pattern is displayed for each system. Basic, voltage, current, and power measurement parameter, harmonic bar graph, harmonic list, and harmonic vector screens
Display Selections screen	Select to display any 4, 8, 16, or 32 of the basic measurement parameters. Display layout: 4, 8, 16, or 32 parameters (4 patterns)
Efficiency and Loss screen	The efficiency and loss obtained by the specified calculation formulas are displayed numerically. Three efficiency and three loss values.
Waveform & Noise screen	Voltage and current waveforms sampled at 500 kHz and noise measurements are displayed compressed on one screen. Trigger: Synchronized with the harmonic sync source Recording length: 1000/5000/10,000/50,000 × All voltage and current channels Compression ratio: 1/1, 1/2, 1/5, 1/10, 1/20, 1/50 (peak-to-peak compression) Recording time:

Recording speed/ Recording length	1000	5000	10,000	50,000
500 kS/s	2 ms	10 ms	20 ms	100 ms
250 kS/s	4 ms	20 ms	40 ms	200 ms
100 kS/s	10 ms	50 ms	100 ms	500 ms
50 kS/s	20 ms	100 ms	200 ms	1000 ms
25 kS/s	40 ms	200 ms	400 ms	2000 ms
10 kS/s	100 ms	500 ms	1000 ms	5000 ms

X-Y Plot screen	Select horizontal and vertical axes from the basic measurement items to display on the X-Y graphs. Dots are plotted at the data update interval, and are not saved. Drawing data can be cleared. Horizontal: 1 data item (gauge display available), Vertical: 2 data items (gauge display available)

-4. Saving Functions

Auto-save function	As the items to be saved, select any measured values including harmonics and noise value data of the FFT function. The selected items are stored to CF card during every measurement interval. (Storage to USB memory is not available.) Can be controlled by timer or real-time clock. Max. no. of saved items: Interval-setting-dependent Data format: CSV format
Manual saving function	Save destinations: USB memory/CF card • Measurement data As the items to be saved, select any measured values including harmonics and noise value data of the FFT function. Pressing the SAVE key saves each measurement value at that moment to the save destination. File format: CSV format • Screen capture The COPY key captures and saves a bitmap image of the display to the save destination. *This function can be used at an interval of 5 sec or more while automatic saving is in progress. File format: Compressed BMP format • Settings data Settings information can be saved/loaded as a settings file. File format: SET format (for PW3390 only) • Waveform data Saves the waveform being displayed by means of [Wave/Noise] display. File format: CSV format

-5. Synchronous Control Function

Function	Synchronous measurements are available by using sync cables to connect Model PW3390 (master/slave). When internal settings match, auto-save is available while synchronized.
Synchronized items	Clock, data update interval (except for FFT calculations), integration start/stop, data reset, certain events
Event items	Hold, manual save, screen capture
Synchronization timing	• Clock, data update interval Within 10 s after power-on by a slave PW3390 • Start/stop, data reset, event Upon key-press and communications operations on the master PW3390
Synchronization delay	Maximum 5 µs per connection. Maximum synchronization delay of an event is +50 ms

-6. Bluetooth® Logger Connectivity

Function	Sends measured values wirelessly to logger by using a Bluetooth® serial conversion adapter.
Supported devices	Hioki LR8410 Link-compatible loggers (LR8410, LR8416)
Sent data	Measured values assigned to the D/A CH9 to CH16 analog output parameters

-7. Other Functions

Display language selection	Japanese, English, Chinese
Beep sound	OFF/ON
Screen color schemes	COLOR1 (black)/2 (blue-green)/3 (blue)/4 (gray)/5 (navy blue)
Start-up screen selection	Wiring or Last-displayed screen (Measurement screens only)
LCD backlight	ON/1 min/5 min/10 min/30 min/60 min
CSV file format	CSV/SSV
Real-time clock function	Auto-calendar, leap-year correcting 24-hour clock
RTC accuracy	±3 s per day @25°C (77°F)
Sensor recognition	Current sensors are automatically recognized when connected (Excluding the CT7000 series sensors)
Warning indicators	When peak over occurs on voltage and current measurement channels, When no sync source is detected Warning indicators for all channels are displayed on all pages of the MEAS screen.
Key-lock	Toggles on/off by holding the ESC key for three seconds.
System reset	Returns all settings to factory defaults
Power-on reset	Returns all settings including language and communications settings, to factory defaults.
File operations	Media content list display, format media, create folders, delete files and folders, copy between storage media

General Specifications

Operating environment	Indoors, Pollution Degree 2, altitude up to 2000 m (6562.20 ft)
Operating temperature and humidity	Temperature: 0°C to 40°C (32°F to 104°F), Humidity: 80% RH or less (no condensation)
Storage temperature and humidity	-10°C to 50°C (14°F to 122°F), 80% RH or less (no condensation)
Dustproof and waterproof	IP30 (EN 60529) (With CF card cover open: IP20)
Applicable standards	Safety EN 61010 EMC EN 61326 Class A
Power supply	100 V to 240 V AC, 50 Hz/60 Hz, Maximum rated power: 140 VA Anticipated transient overvoltage: 2500 V
Backup battery life	Clock, settings and integration values (Lithium battery), Approx. 10 years, @23°C (73°F)
Dimensions	340 mm (13.39 in) W × 170 mm (6.69 in) H × 156 mm (6.14 in) D (excluding protrusions)
Mass	4.6 kg (162.3 oz) with PW3390-03
Product warranty period	1 year
Accessories	Instruction Manual ×1, Measurement Guide ×1, Power cord ×1, USB cable (0.9 m (2.95 ft)) ×1, Input cord label ×2, D-sub connector ×1 (PW3390-02, PW3390-03)

A.7 EIS measurement

N4L Newtons4th Ltd

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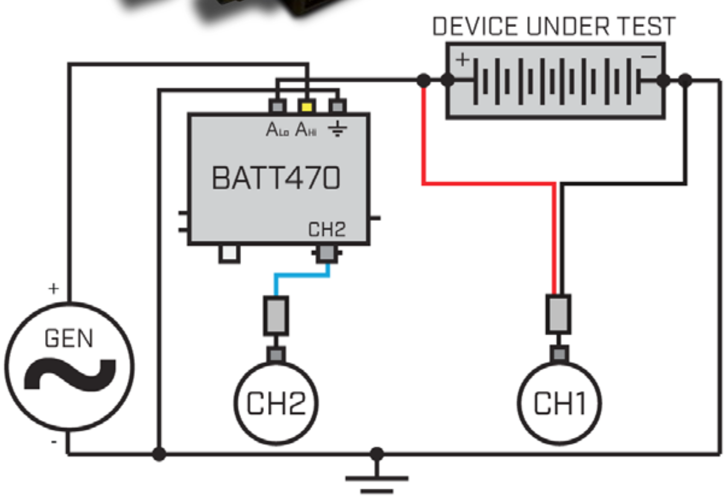
Battery Cell Impedance Measurement (EIS)

PSM3750 FRA + BATT470m

Electrochemical Impedance Analysis Package

ESF10m



BATT470m

The BATT470m Electrochemical Impedance Analysis Package provides a simple to use, wideband impedance analysis solution for the electrochemical market. The BATT470m, coupled with the PSM3750 Frequency Response Analyzer provides impedance measurement of batteries/cells up to 100V DC. With a frequency range of 100mHz to 1MHz, equivalent circuit analysis as well as wideband impedance measurement is quick and simple using PSMComm2 software.

Model	Nominal Resistance	Phase Error	Continuous Current	Voltage Rating	Input Connector
BATT470m	470mΩ ± 0.1%	0.1° / kHz	1Arms	100V DC	4mm, BNC

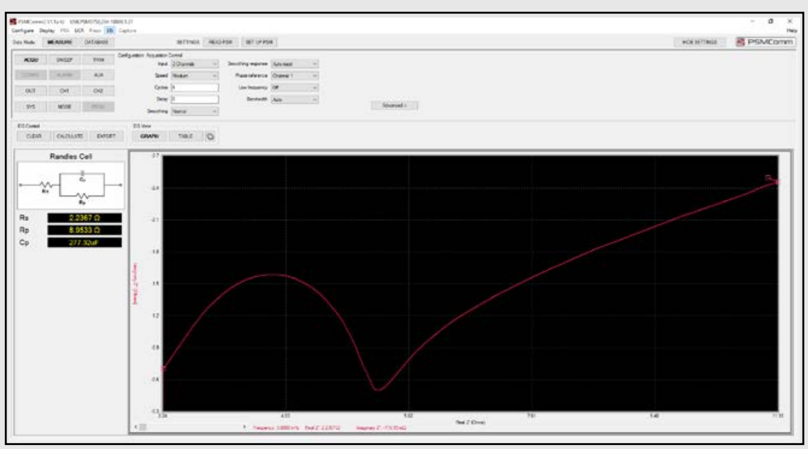
Shunt nominal inductance: < 1nH

CH2 connector: Safety BNC – Non isolated with inverted polarity (Output is at line potential therefore safety BNC to BNC leads must be used for instrument connection)

Protection rating 100V Cat I

EIS Package Consists of:

PSM3750
Batt470m
2x ESF10m

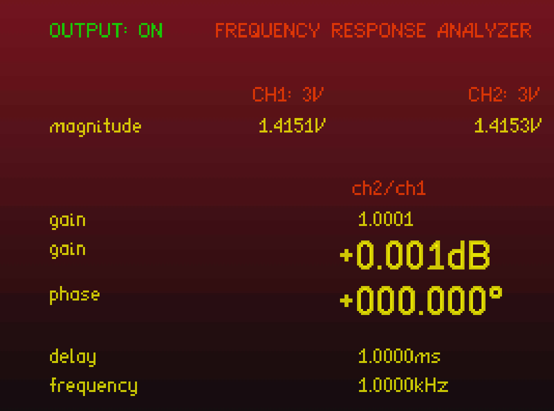


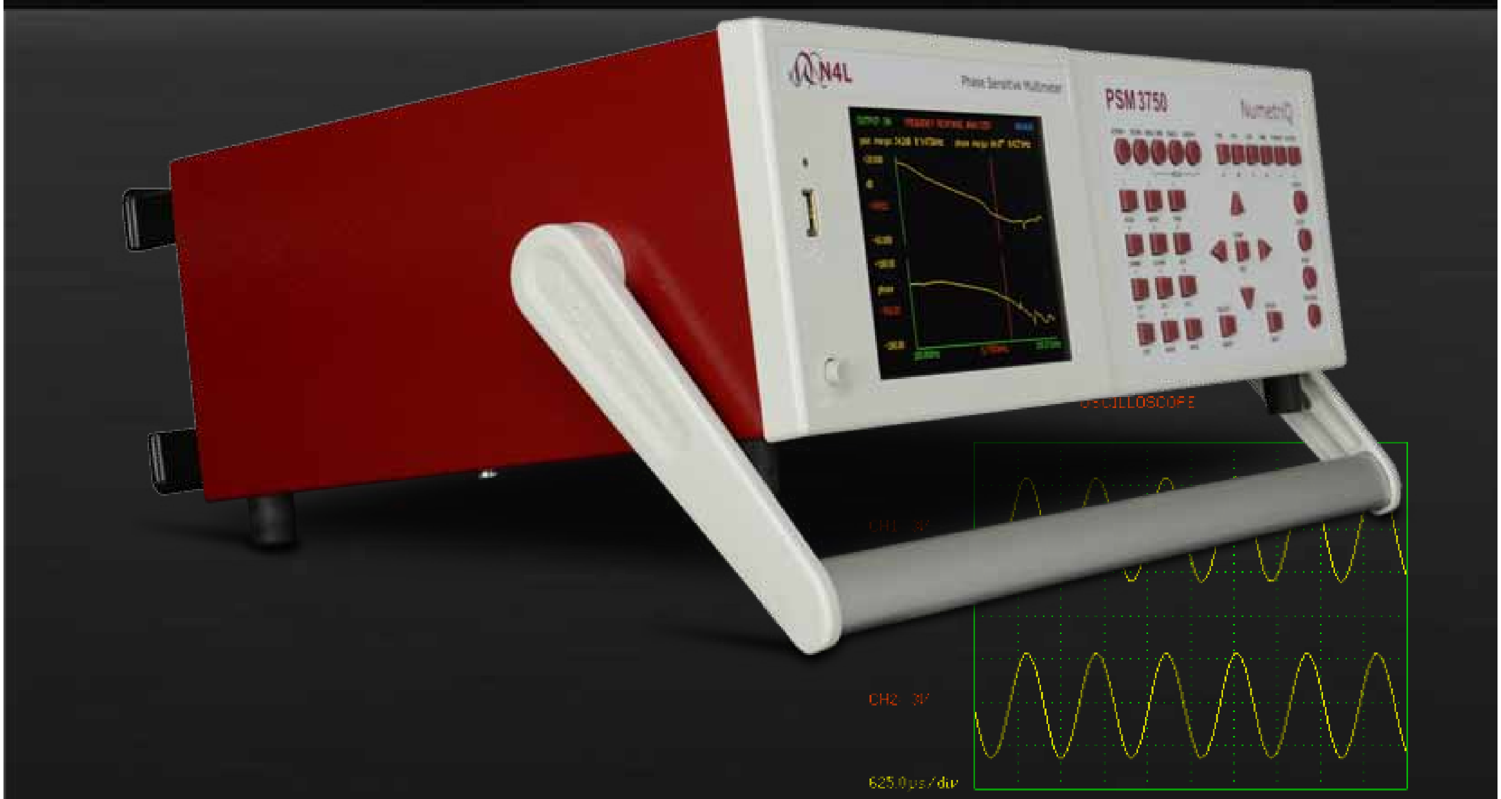
PSMComm2 - EIS Mode (Randles Cell equivalent circuit modelling)

N4L Newtons4th Ltd

Frequency Response Analyzer

PSM3750



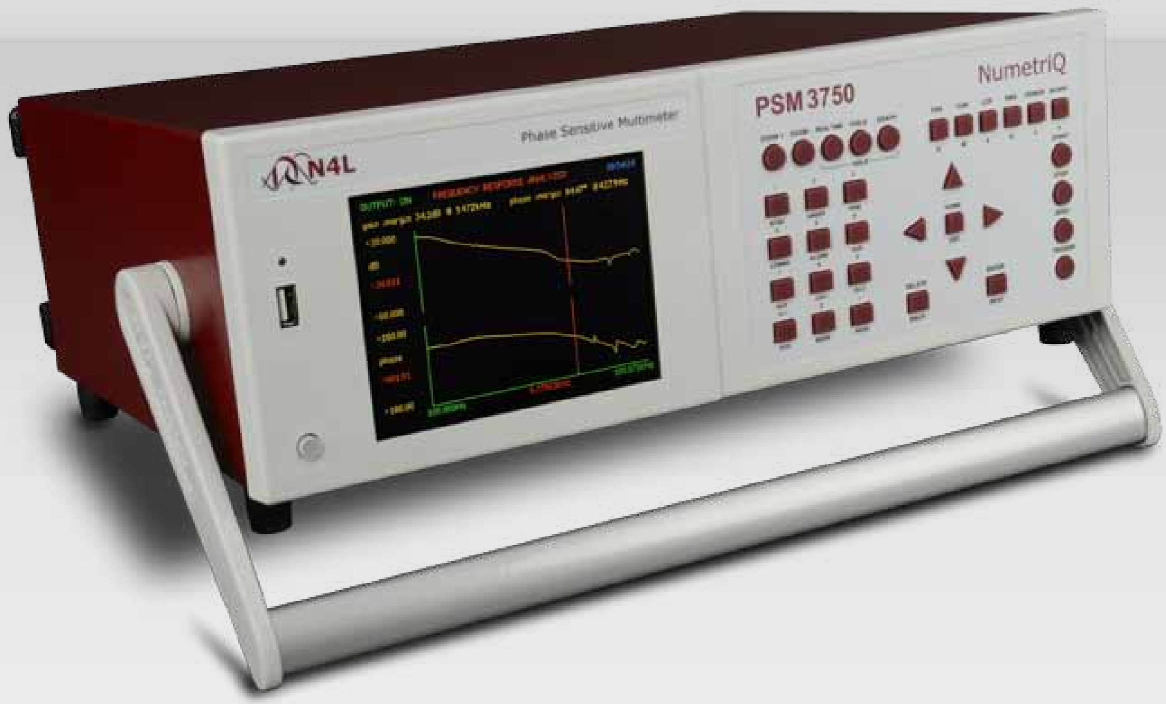


High Accuracy - Wide Bandwidth - 500Vpk Inputs

Leading wideband accuracy	Basic 0.02dB with class leading high frequency performance
Wide frequency range	DC, 10uHz to 50MHz
High Voltage Floating Inputs	Galvanically Isolated fully floating Inputs - 500Vpk range
Fully Isolated Generator	Enables direct connection to feedback loops with no need for isolation transformers
Leading Phase Accuracy	0.025 degrees
Versatile Interfaces	RS232, USB, LAN and GPIB
PC Software Options	Remote control, tables, graphs and database management of results
Various Measurement Modes	FRA, PAV, POWER, LCR, RMS Voltmeter, Scope

Frequency Response Analysis

The PSM3750 offers a complete solution for high frequency, high accuracy frequency response measurements. Featuring a unique 10Vrms output, 500Vpk isolated generator and 500Vpk isolated inputs the PSM3750 is an innovative step forward in frequency response measurement. The PSM3750 also offers market leading gain and phase accuracy (0.01dB, 0.025deg) for an isolated input frequency response analyzer.

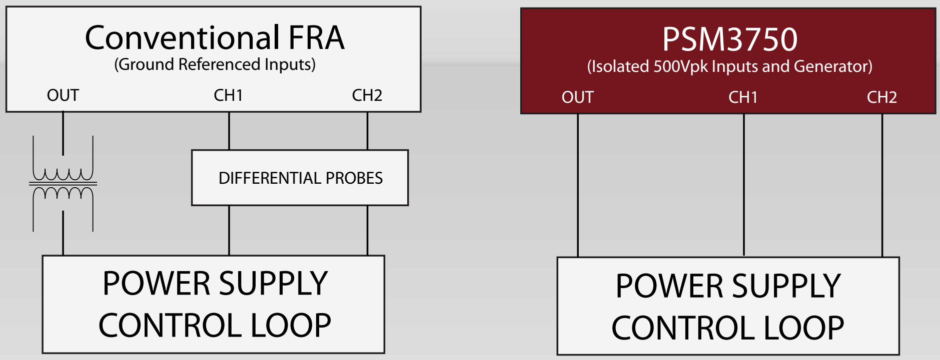


Impedance Analysis with the IAI2

When combined with the IAI2 (Impedance Analysis Interface) the PSM3750 provides an accurate solution for LCR measurements, using a true 4 wire Kelvin technique without the need for external shunts. The IAI2 has a bandwidth up to 50MHz, with a wide measurement range this technology builds on years of expertise Newtons4th has gained in the impedance measurement field.

Isolation for High Voltage Feedback Loop Analysis

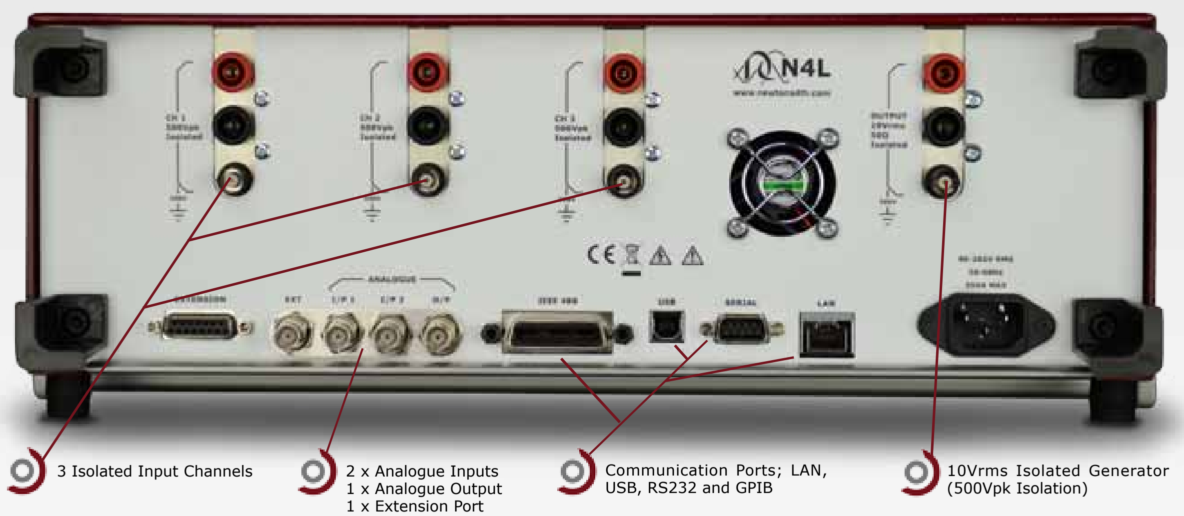
The PSM3750 features a 500Vpk isolated generator, this enables the engineer to connect directly to the feedback loop with no need for an injection transformer. This has been made possible through the development of a truly isolated generator card providing DC & 10uHz up to 50MHz injection bandwidth. In most cases there will be no requirement for attenuators due to the presence of 500Vpk isolated inputs, making feedback analysis simple, fast and flexible.



As illustrated above, the PSM3750 eliminates the requirement for an isolation transformer and differential probes. Another disadvantage when using conventional FRA instruments whilst performing analysis over a wide frequency band is that many different isolation transformers will be required for the different frequency ranges of the test. The PSM3750 eliminates this problem and generates frequencies throughout its entire frequency range from a single output.

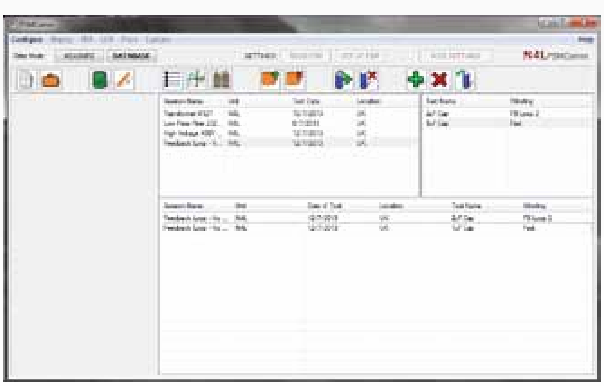
Connections

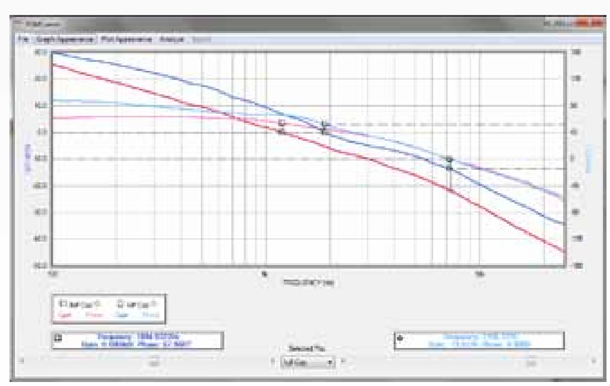
The rear of the PSM3750 features up to 3 isolated input channels and an isolated generator. All 3 input channels and the output channel offer both BNC and 4mm safety connectors. With LAN, RS232, GPIB and USB offered as standard, the PSM3750 is equipped for all modern communication environments.



Software - PSMComm2

The PSM3750 is supplied with a free comprehensive software package, PSMComm2. This enables the user to perform multiple sweeps during development and compare the sweeps on one single plot. PSMComm2 also includes a database function in which the user can store their projects and organise large amounts of data in a managable, structured format.





MEASUREMENT SPECIFICATION

Frequency Response Analyser	
Measurement	Magnitude, Gain (CH1/CH2, CH2/CH1), Gain (dB), offset gain (dB), phase(°)
Frequency Range	10uHz - 50MHz
Gain Accuracy in dB	0.01dB + 0.1dB/MHz <5MHz 0.31dB + 0.04dB/MHz < 50MHz
Phase Accuracy	0.025° < 10kHz 0.05deg + 0.00015deg/kHz < 50MHz
Frequency Source	Generator or CH1 Input
Measurement	Real Time DFT, no missing data
Speed	Up to 100 reading per second
Filter	Selectable from 0.2 seconds
Phase Angle Voltmeter	
Measurement	In Phase, Quadrature, Tan Ø, Magnitude, Phase, in-phase ratio, rms, rms ratio, LVDT differential, LVDT ratiometric
Frequency Range	10uHz - 50MHz
Basic Accuracy (AC)	0.075% range + 0.075% reading + 50uV < 10kHz 0.075% range + 0.25% + 0.001%/kHz rdg + 50uV < 1MHz 0.075% range + 0.01% +0.00025%/kHz rdg + 50uV < 50MHz
L C R Meter	
Functions	L, C, R (AC), Q, Tan Delta, Impedance, Phase - Series or Parallel Circuit
Frequency Range	10uHz - 50MHz
Current Shunt	External or Optional IAI2 Impedance Interface
Ranges (External Shunt)	Inductance 1uH to 100H Capacitance 100pF to 100uF Resistance 1Ω to 1MΩ
Basic Accuracy	0.1% + Tolerance of Shunt
Sweep Capability	all AC functions
True RMS Voltmeter	
Channels	2 (Optional 3rd Channel Available)
Frequency Range	DC to 5MHz 5MHz to 50MHz fundamental only
Measurement	RMS, AC, DC, Peak, CF, Surge, dBm
Basic Accuracy (AC)	As PAV + 0.05mV
Basic Accuracy (DC)	0.1% range + 0.1% reading + 0.5mV
Power Meter	
Measurements	W, VA, PF, V, A, - Total, Fundamental and Integrated, Power Harmonics
Frequency Range	DC & 10mHz to 5MHz 5MHz to 50MHz fundamental only
Current Shunt	External
Current Accuracy	As Voltage + External Shunt Tolerance
Watts Accuracy	0.1% VA range + 0.1% reading + external shunt tolerance
Signal Generator	
Type	Fully isolated 10Vrms output protected to 500Vpk. Direct Digital Synthesis
Frequency	10uHz to 50MHz
Waveforms	Sine, Square, Triangle, Sawtooth, White Noise
Accuracy (no trim)	Frequency ±0.05% Amplitude ±5% < 10MHz, Amplitude ±10% < 50MHz
Impedance	50 Ohm ± 2% / 100pF to Chassis
Output Level	35mVrms to 10Vrms
Offset	±10Vdc, Resolution 20mV
Harmonic Analyser	
Scan	Single or Series
Frequency Range	20mHz to 5MHz 5MHz to 50MHz Fundamental only
Measurement	Harmonic, Series THD, Difference THD
Max Harmonic	100

Input Ranges	
Differential Inputs	2 or 3 x Isolated Inputs 500Vpk
Connectors	Isolated BNC
Coupling	AC+DC, AC (<10VDC), AC (<500VDC)
Max Common Mode	500Vpk from earth
Input Ranges	3mV, 10mV, 30mV, 100mV, 300mV, 1V, 3V, 10V, 30V, 100V, 300V, 500V, 300mV*, 1V*, 3V*, 10V* *High Voltage Attenuator
Scaling	1x10^-9 to 1x10^9
Ranging	Full auto, Up only or Manual
Input Impedance	1M Ohm Differential / 100pF to Chassis

Model Numbers

Available Packages	
PSM3750-2CH	2 Channel PSM3750
PSM3750-3CH	3 Channel PSM3750
PSM3750-2CH+IAI2	2 Channel PSM3750 + IAI2
PSM3750-3CH+IAI2	3 Channel PSM3750 + IAI2

IAI2 - Impedance Analysis Interface

Specification		
Frequency Range	10uHz to 50MHz	
Measurement Parameters	L, C, R, Z, Phase, QF, Tan(δ), Series and Parallel circuit	
Measurement Ranges	10nH to 10kH, 1pF to 1000uF, 1mΩ to 500MΩ	
Basic Accuracy + Phase Accuracy	0.1% < 1kHz 0.2% + 0.002%/kHz < 1MHz 0.2% + 0.0005%/kHz < 35MHz 0.2% + 0.001%/kHz < 50MHz	Low Shunt 0.1° + 0.01°/kHz Med Shunt 0.05° + 0.005°/kHz High Shunt 0.05° + 0.005°/kHz V.High Shunt 0.1° + 0.05°/kHz
Internal Shunts	5Ω, 50Ω, 5kΩ, 500kΩ	

ACCESSORIES AND PORTS

Accessories	
Probes	4 off with 2 Channel, 6 off with 3 Channel
Leads	Output, RS232, Power
Software	CommView, PSMComm2
Documentation	Calibration Certificate, User Manual
Ports	
RS232	Baud Rate to 19200, RTS/CTS flow Control
Analog Output	Bipolar ±10V on any measured function - BNC
Sync output	Pulse synchronised to generator
Extension Ports (N4L accessories)	2 15 pin female D type
LAN (Standard)	10/100 base-T Ethernet auto sensing RJ45
GPIB (Standard)	IEEE488.2 Compatible

SYSTEM SPECIFICATIONS

Datalog	
Functions	Up to 4 measured functions, user selectable
Datalog Window	From 10ms with no gap between each log
Memory	RAM or Non-Volatile Memory up to 16,000 records
General	
Display	320 x 240 QVGA full colour TFT, White LED backlit
Dimension	130H x 400W x 315D mm excluding feet
Weight	3.3kg (2Channel), 3.5kg (3Channel)
Program Stores	100, Location 1 loaded on power up
Sweep Stores	2000, all parameters in any sweep function
Remote Operation	Full Capability, Control and Data
Temperature	5 to 40°C ambient temperature, 20 to 90% non-condensing RH
Power Supply	90-264Vrms 47-63Hz 30VA max
CMRR	140dB @ 240Vrms - 50Hz, 120dB @ 100Vrms - 1kHz
Warranty	3 Years

All specifications at 23°C ± 5°C . These specifications are quoted in good faith but Newtons4th Ltd reserves the right to amend any specification at any time without notice

Newtons4th

Contact your local N4L Distributor for further details

Newtons4th Ltd (abbreviated to N4L) was established in 1997 to design, manufacture and support innovative electronic equipment to a worldwide market, specialising in sophisticated test equipment particularly related to phase measurement. The company was founded on the principle of using the latest technology and sophisticated analysis techniques in order to provide our customerswith accurate, easy to use instruments at a lower price than has been traditionally associated with these types of measurements

Flexibility in our products and an attitude to providing the solutions that our customers really want has allowed us to develop many innovative functions in our ever increasing product range

Newtons4th Ltd are ISO9001 registered, the internationally recognised standard for the quality management of businesses

In recognition of the technical innovation and commercial success of the PPA series, N4L received the "Innovation 2010" Queen's award for enterprise

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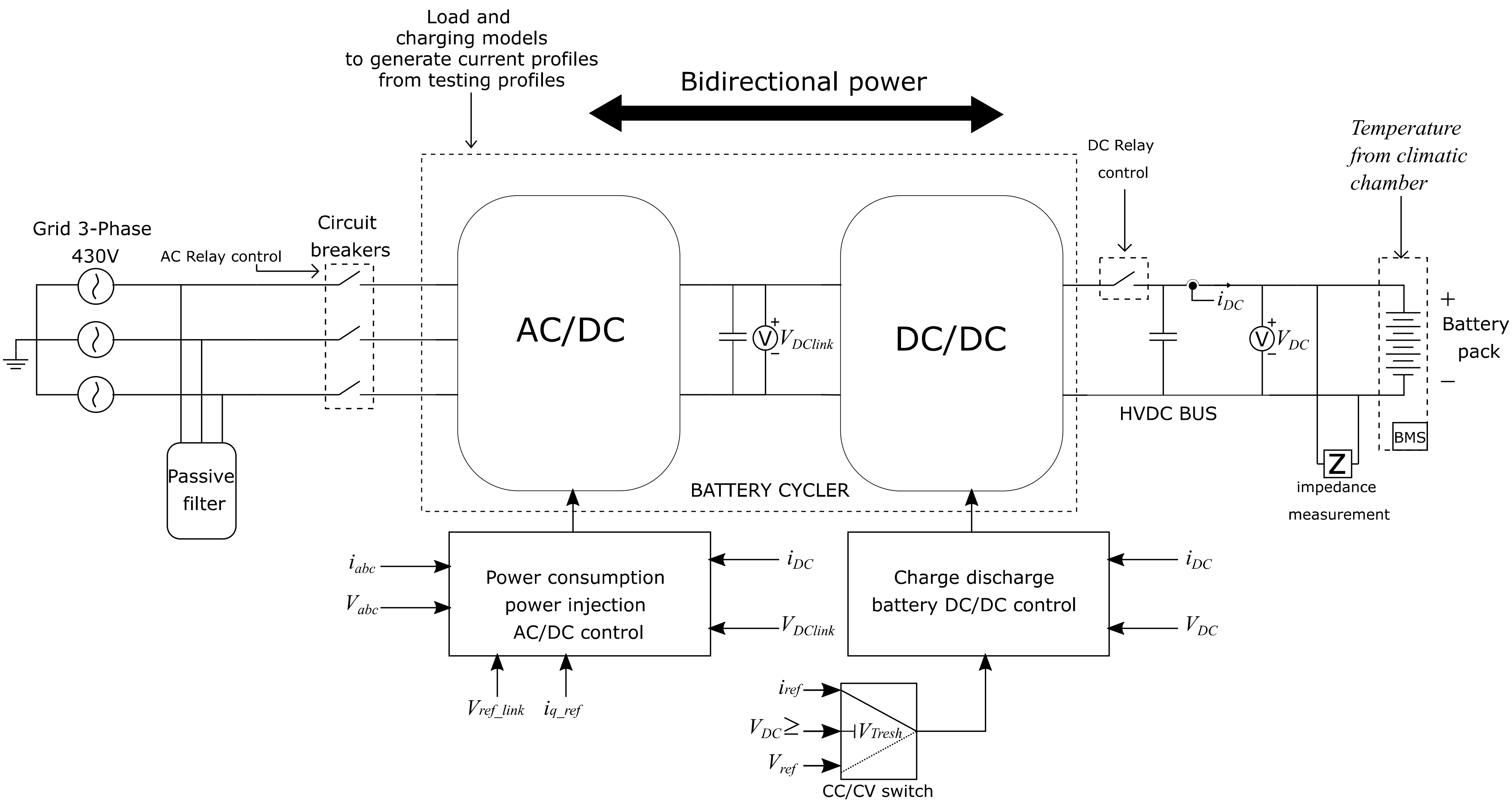
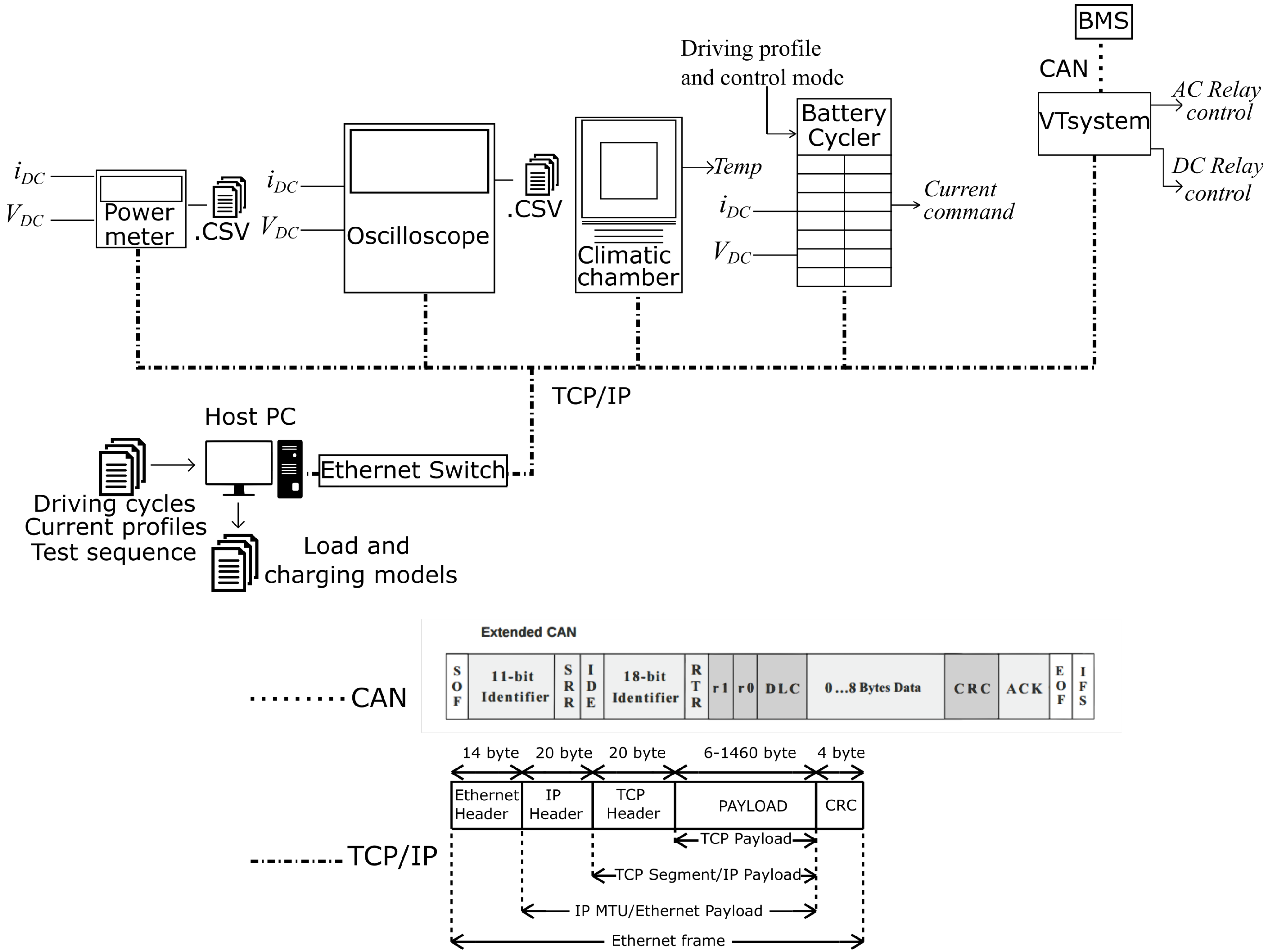
A.8 Power circuit diagram


Load and
charging models
to generate current profiles
from testing profiles
Bidirectional power
Grid 3-Phase
430V
AC Relay control
Circuit
breakers
Passive
filter
AC/DC
DC/DC
V_{DClink}
BATTERY CYCLER
DC Relay
control
i_{DC}
V_{DC}
HVDC BUS
Temperature
from climatic
chamber
+
Battery
pack
–
BMS
Z
impedance
measurement
i_{abc}
V_{abc}
Power consumption
power injection
AC/DC control
i_{DC}
V_{DClink}
V_{ref_link}
i_{q_ref}
Charge discharge
battery DC/DC control
i_{DC}
V_{DC}
i_{ref}
$V_{DC} \geq$
V_{Tresh}
V_{ref}
CC/CV switch

A.9 Communication and equipment control diagram



i_{DC}
V_{DC}
Power meter
.CSV
Oscilloscope
Climatic chamber
Temp
Driving profile and control mode
Battery Cycler
Current command
BMS
CAN
VTsystem
AC Relay control
DC Relay control
TCP/IP
Host PC
Ethernet Switch
Driving cycles
Current profiles
Test sequence
Load and charging models
CAN
TCP/IP
Extended CAN
SOF
11-bit Identifier
SRR
IDE
18-bit Identifier
RTR
r1
r0
DLC
0…8 Bytes Data
CRC
ACK
EOF
IFS
14 byte
20 byte
20 byte
6-1460 byte
4 byte
Ethernet Header
IP Header
TCP Header
PAYLOAD
CRC
TCP Payload
TCP Segment/IP Payload
IP MTU/Ethernet Payload
Ethernet frame

Appendix B

Tehcnical specifications of driving cycles

Passenger Cars and Light-duty Trucks

A.1 New European Driving Cycle for Passenger Cars and Light-Duty Trucks—NEDC

From year 2000, the cycle is run with the engine cold started (MVEG-B). Previously, there was a 40-s warm-up idling period. Cycle with constant accelerations, prolonged cruise and simple structure. In this form, valid from 1992 to 2017 (Fig. A.1 and Table A.1).

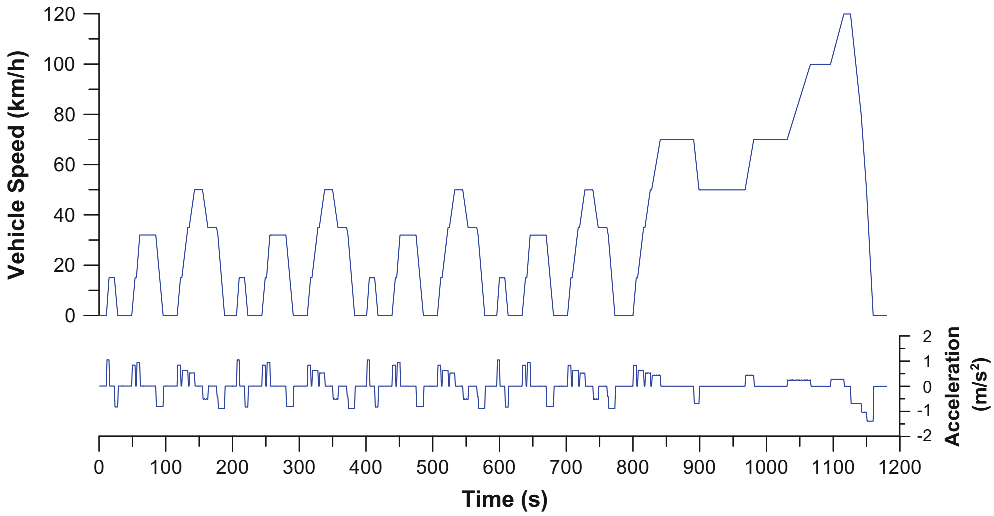


Fig. A.1 Vehicle speed and acceleration versus time of the European NEDC

Table A.1 Technical specifications of the European NEDC

Distance (m)/Duration (s or min)	11,000	1180 (19.67)
Maximum/Average vehicle speed (km/h)	120.00	33.56
Average driving speed (km/h)/Speed σ (km/h)	44.00	30.96
Average/Maximum acceleration (m/s^2)	0.594	1.042
Average/Minimum deceleration (m/s^2)	−0.789	−1.389
Driving time (s)/(%)	900	76.27
Driving time (%) $V \leq 30$ km/h/$30 < V \leq 60$ km/h	46.44	33.81
Driving time (%) $60 < V \leq 100$ km/h/$V > 100$ km/h	16.61	3.14
Cruising time (s)/(%)	467	39.58
Time spent accelerating (s)/(%)	247	20.93
Acceleration time (%) $0 < a \leq 1.0$ m/s^2/$a > 1.0$ m/s^2	19.58	1.35
Time spent decelerating (s)/(%)	186	15.76
Decel. time (%) $a < -1.0$ m/s^2/$-1.0 \leq a < 0$ m/s^2	1.53	14.24
Idling time (s)/(%)	280	23.73 (24.83)
No. of accelerations/Positive acceleration σ (m/s^2)	31	0.252
Accelerations per km/per min	2.82	1.58
Number of stops/Max. interm. stop duration (s)	14	27
Stops per km/Average stop duration (s)	1.27	20.00
RPA (m/s^2)/PKE (m/s^2)	0.116	2.890

A.4 European ARTEMIS Urban

Part of the ARTEMIS-project cycles, this schedule is a much more realistic (than the legislated NEDC) simulation of the actual driving conditions in a European city (Fig. A.4 and Table A.4).

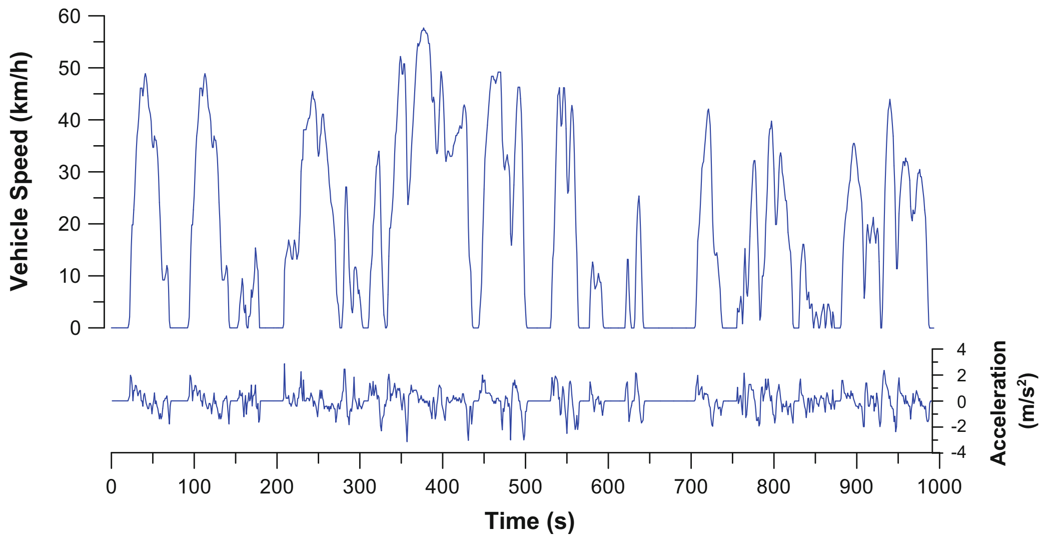


Fig. A.4 Vehicle speed and acceleration versus time of the ARTEMIS Urban

Table A.4 Technical specifications of the ARTEMIS Urban

Distance (m)/Duration (s or min)	4869.8	993 (16.55)
Maximum/Average vehicle speed (km/h)	57.70	17.65
Average driving speed (km/h)/Speed σ (km/h)	23.92	17.01
Average/Maximum acceleration (m/s^2)	0.732	2.861
Average/Minimum deceleration (m/s^2)	−0.782	−3.139
Driving time (s)/(%)	733	73.82
Driving time (%) V < 30 km/h/30 < V < 60 km/h	70.59	29.41
Driving time (%) 60 < V < 100 km/h/V > 100 km/h	0	0
Cruising time (s)/(%)	67	6.75
Time spent accelerating (s)/(%)	344	34.64
Acceleration time (%) 0 < a $\leq$ 1.0 m/s^2/a > 1.0 m/s^2	25.68	8.96
Time spent decelerating (s)/(%)	322	32.42
Decel. time (%) a < −1.0 m/s^2/−1.0 $\leq$ a < 0 m/s^2	9.77	22.66
Idling time (s)/(%)	260	26.18 (30.41)
No. of accelerations/Positive acceleration σ (m/s^2)	46	0.536
Accelerations per km/per min	9.45	2.78
Number of stops/Max. interm. stop duration (s)	14	61
Stops per km/Average stop duration (s)	2.87	18.57
RPA (m/s^2)/PKE (m/s^2)	0.342	8.117

A.5 European ARTEMIS Rural Road

Part of the ARTEMIS-project cycles; simulates driving in rural roads (Fig. A.5 and Table A.5).

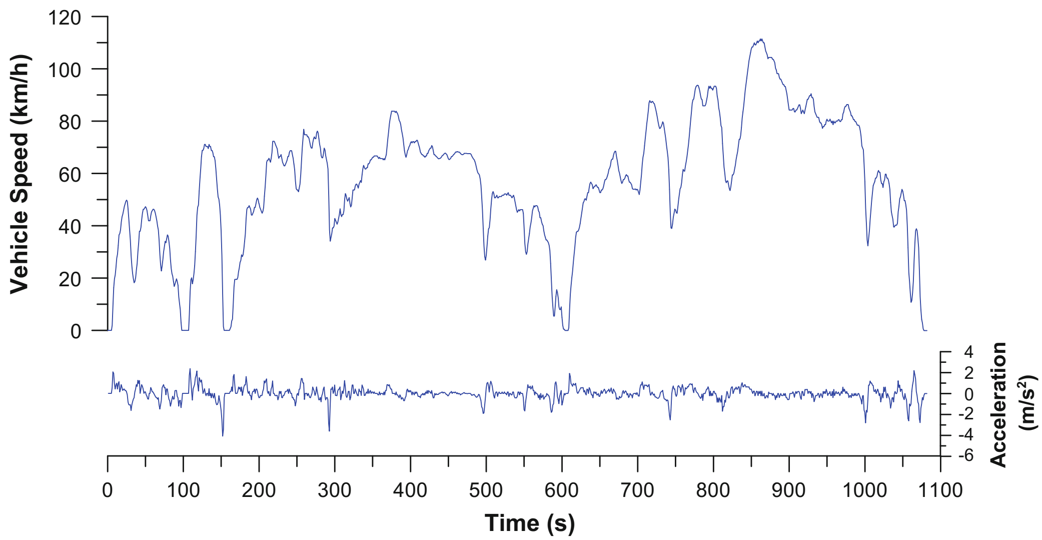


Fig. A.5 Vehicle speed and acceleration versus time of the ARTEMIS rural road

Table A.5 Technical specifications of the ARTEMIS rural road

Distance (m)/Duration (s or min)	17,272.5	1082 (18.03)
Maximum/Average vehicle speed (km/h)	111.50	57.46
Average driving speed (km/h)/Speed σ (km/h)	59.05	24.55
Average/Maximum acceleration (m/s^2)	0.494	2.361
Average/Minimum deceleration (m/s^2)	−0.516	−4.083
Driving time (s)/(%)	1053	97.32
Driving time (%) $V \leq 30$ km/h/$30 < V \leq 60$ km/h	13.31	37.43
Driving time (%) $60 < V \leq 100$ km/h/$V > 100$ km/h	45.84	3.42
Cruising time (s)/(%)	174	16.08
Time spent accelerating (s)/(%)	449	41.50
Acceleration time (%) $0 < a \leq 1.0$ m/s^2/$a > 1.0$ m/s^2	37.71	3.79
Time spent decelerating (s)/(%)	430	39.74
Decel. time (%) $a < -1.0$ m/s^2/$-1.0 \leq a < 0$ m/s^2	5.08	34.66
Idling time (s)/(%)	29	2.68 (3.51)
No. of accelerations/Positive acceleration σ (m/s^2)	43	0.399
Accelerations per km/per min	2.49	2.38
Number of stops/Max. interm. stop duration (s)	5	9
Stops per km/Average stop duration (s)	0.29	5.80
RPA (m/s^2)/PKE (m/s^2)	0.182	4.571

A.6 European ARTEMIS Motorway 150

Part of the ARTEMIS-project cycles; simulates highway driving. There is also a version with maximum speed 130 km/h (Fig. A.6 and Table A.6).

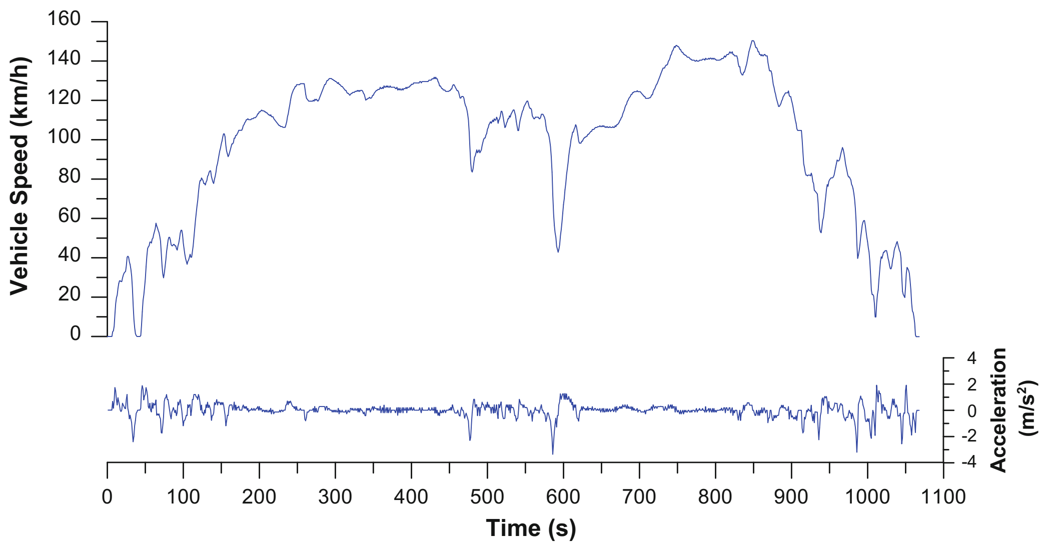


Fig. A.6 Vehicle speed and acceleration versus time of the ARTEMIS Motorway 150

Table A.6 Technical specifications of the ARTEMIS Motorway 150

Distance (m)/Duration (s or min)	29,545.0	1068 (17.8)
Maximum/Average vehicle speed (km/h)	150.40	99.59
Average driving speed (km/h)/Speed σ (km/h)	100.91	37.58
Average/Maximum acceleration (m/s^2)	0.426	1.917
Average/Minimum deceleration (m/s^2)	−0.509	−3.361
Driving time (s)/(%)	1054	98.69
Driving time (%) $V \leq 30$ km/h/$30 < V \leq 60$ km/h	6.37	13.95
Driving time (%) $60 < V \leq 100$ km/h/$V > 100$ km/h	14.23	65.45
Cruising time (s)/(%)	268	25.09
Time spent accelerating (s)/(%)	428	40.07
Acceleration time (%) $0 < a \leq 1.0$ m/s^2/$a > 1.0$ m/s^2	36.99	3.09
Time spent decelerating (s)/(%)	358	33.52
Decel. time (%) $a < -1.0$ m/s^2/$-1.0 \leq a < 0$ m/s^2	3.93	29.59
Idling time (s)/(%)	14	1.31 (1.78)
No. of accelerations/Positive acceleration σ (m/s^2)	39	0.345
Accelerations per km/per min	1.32	2.19
Number of stops/Max. interm. stop duration (s)	3	4
Stops per km/Average stop duration (s)	0.10	4.67
RPA (m/s^2)/PKE (m/s^2)	0.134	3.423

A.7 European ARTEMIS Urban-Road-Motorway 150

Part of the ARTEMIS-project cycles. This is the entire cycle with urban, rural and motorway parts. Very long distance (approx. 52 km) and duration (more than 52 min), and very high maximum vehicle speed (Fig. A.7 and Table A.7).

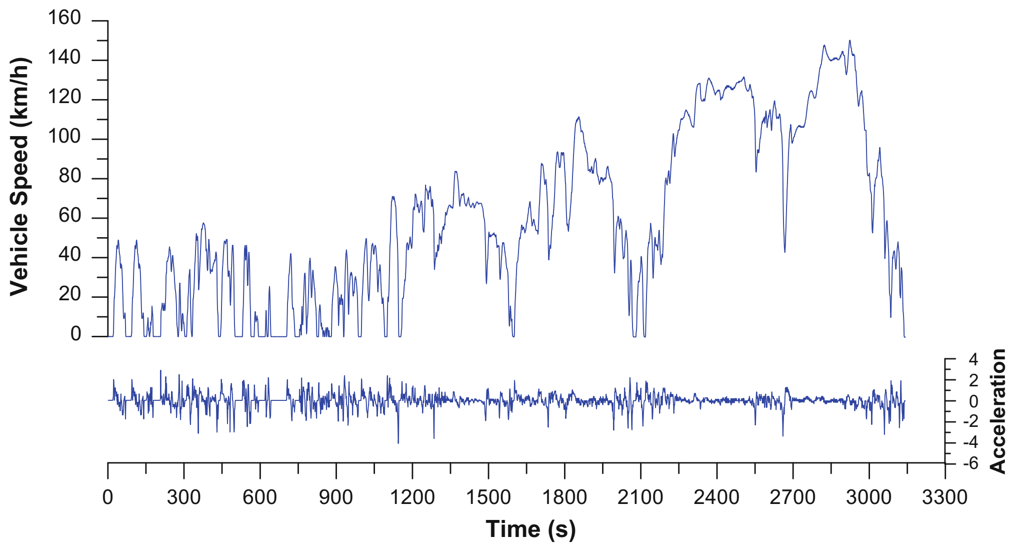


Fig. A.7 Vehicle speed and acceleration versus time of the ARTEMIS Urban-Rural-Motorway 150

Table A.7 Technical specifications of the ARTEMIS Urban-Rural-Motorway 150

Distance (m)/Duration (s or min)	51,687.4	3143 (52.38)
Maximum/Average vehicle speed (km/h)	150.40	59.20
Average driving speed (km/h)/Speed σ (km/h)	65.52	43.35
Average/Maximum acceleration (m/s^2)	0.537	2.861
Average/Minimum deceleration (m/s^2)	−0.591	−4.083
Driving time (s)/(%)	2840	90.36
Driving time (%) V $\leq$ 30 km/h/30 < V $\leq$ 60 km/h	29.05	26.92
Driving time (%) 60 < V $\leq$ 100 km/h/V > 100 km/h	20.62	23.42
Cruising time (s)/(%)	509	16.19
Time spent accelerating (s)/(%)	1221	38.84
Acceleration time (%) 0 < a $\leq$ 1.0 m/s^2/a > 1.0 m/s^2	33.66	5.19
Time spent decelerating (s)/(%)	1110	35.32
Decel. time (%) a < −1.0 m/s^2/−1.0 $\leq$ a < 0 m/s^2	6.17	29.14
Idling time (s)/(%)	303	9.64 (11.42)
No. of accelerations/Positive acceleration σ (m/s^2)	128	0.444
Accelerations per km/per min	2.48	2.44
Number of stops/Max. interm. stop duration (s)	20	61
Stops per km/Average stop duration (s)	0.39	15.15
RPA (m/s^2)/PKE (m/s^2)	0.170	4.249

A.9 U.S. FTP-75 Cycle for Passenger Cars and Light-Duty Trucks

Derived from the FTP-72 by adding a third hot-started phase of 505 s, identical to the first (cold-started) one. The third phase starts after the engine has stopped for 10 minutes. Valid from model year 1975 (Fig. A.9 and Table A.9).

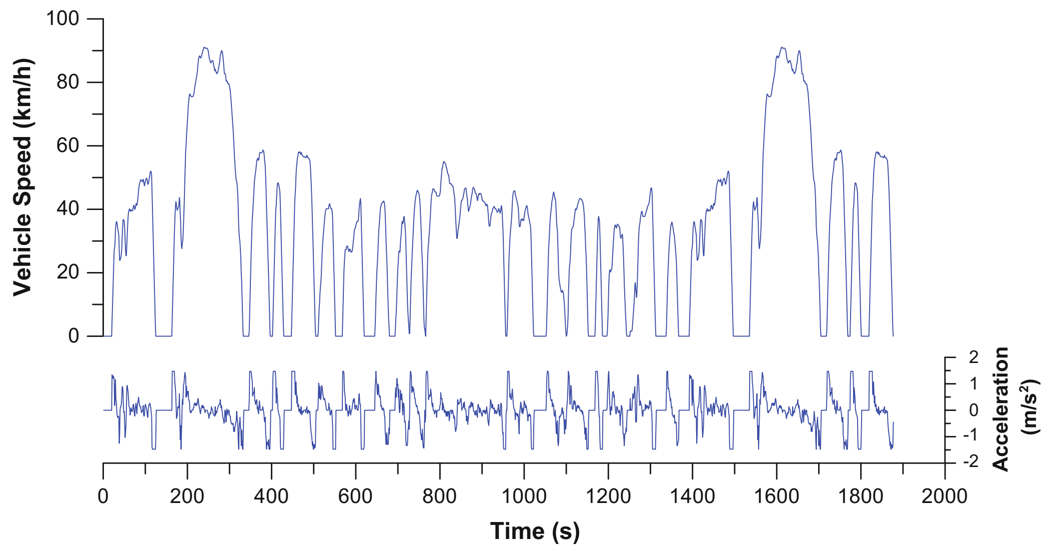


Fig. A.9 Vehicle speed and acceleration versus time of the U.S. FTP-75

Table A.9 Technical specifications of the U.S. FTP-75

Distance (m)/Duration (s or min)	17,769.4	1877 (31.28)
Maximum/Average vehicle speed (km/h)	91.25	34.08
Average driving speed (km/h)/Speed σ (km/h)	41.57	25.67
Average/Maximum acceleration (m/s^2)	0.511	1.475
Average/Minimum deceleration (m/s^2)	−0.576	−1.475
Driving time (s)/(%)	1539	81.99
Driving time (%) $V \leq 30$ km/h/$30 < V \leq 60$ km/h	40.65	47.20
Driving time (%) $60 < V \leq 100$ km/h/$V > 100$ km/h	12.15	0
Cruising time (s)/(%)	145	7.73
Time spent accelerating (s)/(%)	739	39.37
Acceleration time (%) $0 < a \leq 1.0$ m/s^2/$a > 1.0$ m/s^2	32.34	7.03
Time spent decelerating (s)/(%)	655	34.90
Decel. time (%) $a < -1.0$ m/s^2/$-1.0 \leq a < 0$ m/s^2	8.79	26.11
Idling time (s)/(%)	338	18.01 (19.61)
No. of accelerations/Positive acceleration σ (m/s^2)	78	0.463
Accelerations per km/per min	4.39	2.49
Number of stops/Max. interm. stop duration (s)	19	38
Stops per km/Average stop duration (s)	1.07	17.79
RPA (m/s^2)/PKE (m/s^2)	0.184	4.508

A.11 U.S. SFTP US06

Supplemental, to the FTP-75, US06 simulates aggressive, high-speed and high-acceleration driving behavior on a motorway; based on data from driving conditions in Baltimore, Atlanta, Los Angeles and Spokane in the early 90s. Among the cycles with the highest vehicle speed and acceleration. Implemented gradually from 2000 (Fig. A.11 and Table A.11).

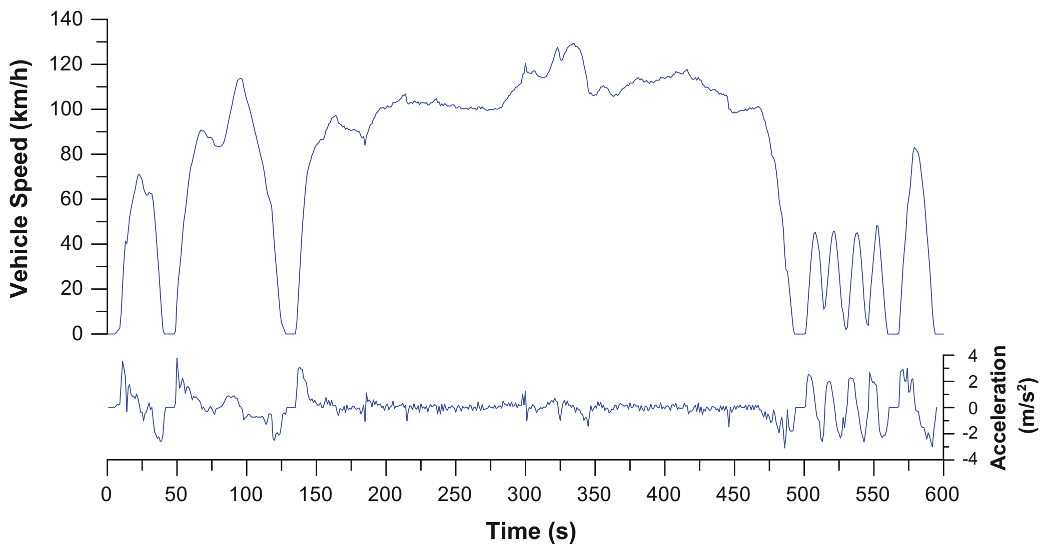


Fig. A.11 Vehicle speed and acceleration versus time of the U.S. SFTP US06

Table A.11 Technical specifications of the U.S. SFTP US06

Distance (m)/Duration (s or min)	12,887.6	600 (10)
Maximum/Average vehicle speed (km/h)	129.23	77.33
Average driving speed (km/h)/Speed σ (km/h)	82.70	39.44
Average/Maximum acceleration (m/s^2)	0.670	3.755
Average/Minimum deceleration (m/s^2)	−0.728	−3.085
Driving time (s)/(%)	561	93.50
Driving time (%) V $\leq$ 30 km/h/30 < V $\leq$ 60 km/h	18.50	10.67
Driving time (%) 60 < V $\leq$ 100 km/h/V > 100 km/h	26.17	44.67
Cruising time (s)/(%)	33	5.50
Time spent accelerating (s)/(%)	275	45.83
Acceleration time (%) 0 < a $\leq$ 1.0 m/s^2/a > 1.0 m/s^2	35.33	10.50
Time spent decelerating (s)/(%)	253	42.17
Decel. time (%) a < −1.0 m/s^2/−1.0 $\leq$ a < 0 m/s^2	11.50	30.67
Idling time (s)/(%)	39	6.50 (7.83)
No. of accelerations/Positive acceleration σ (m/s^2)	34	0.815
Accelerations per km/per min	2.64	3.40
Number of stops/Max. interm. stop duration (s)	6	7
Stops per km/Average stop duration (s)	0.47	6.50
RPA (m/s^2)/PKE (m/s^2)	0.222	5.454

A.20 Japanese JC08

Highly transient with minimum cruising time (in contrast to its predecessor, the J10-15) but long idling period, indicative of heavy congestion in a Japanese big city. Emission measurements conducted twice, once with a cold start (25% weighting) and once with a hot start (75%). Fully phased-in from October 2011 (Fig. A.20 and Table A.20).

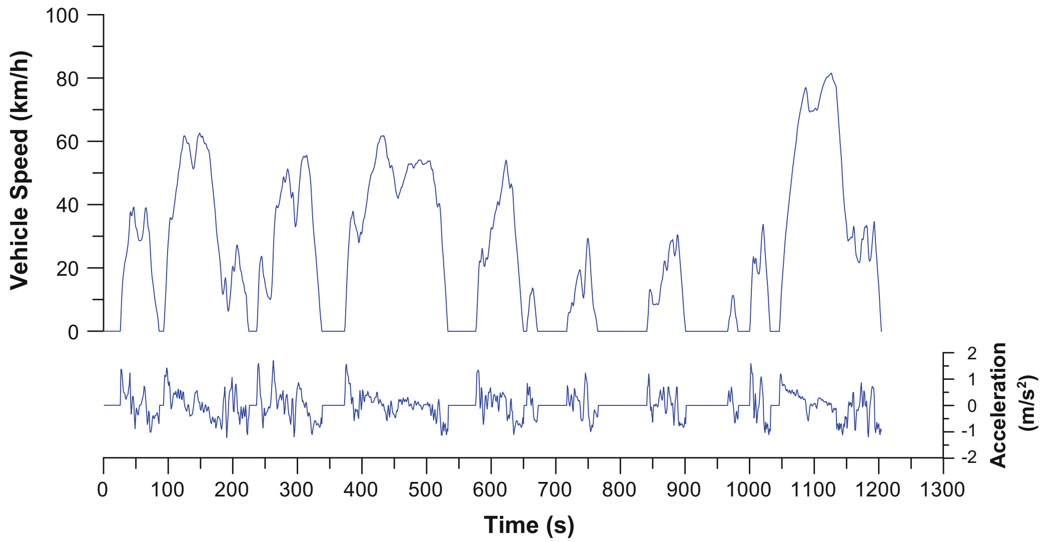


Fig. A.20 Vehicle speed and acceleration versus time of the Japanese JC08

Table A.20 Technical specifications of the Japanese JC08

Distance (m)/Duration (s or min)	8159.4	1204 (20.07)
Maximum/Average vehicle speed (km/h)	81.60	24.40
Average driving speed (km/h)/Speed σ (km/h)	34.24	23.08
Average/Maximum acceleration (m/s^2)	0.426	1.694
Average/Minimum deceleration (m/s^2)	−0.458	−1.222
Driving time (s)/(%)	858	71.26
Driving time (%) $V \leq 30$ km/h/30 < $V \leq 60$ km/h	62.13	30.23
Driving time (%) 60 < $V \leq 100$ km/h/V > 100 km/h	7.64	0
Cruising time (s)/(%)	18	1.50
Time spent accelerating (s)/(%)	435	36.13
Acceleration time (%) 0 < $a \leq 1.0$ m/s^2/a > 1.0 m/s^2	33.22	2.91
Time spent decelerating (s)/(%)	405	33.64
Decel. time (%) a < −1.0 m/s^2/−1.0 $\leq$ a < 0 m/s^2	1.66	31.97
Idling time (s)/(%)	346	28.74 (29.65)
No. of accelerations/Positive acceleration σ (m/s^2)	46	0.342
Accelerations per km/per min	5.64	2.29
Number of stops/Max. interm. stop duration (s)	11	76
Stops per km/Average stop duration (s)	1.35	31.45
RPA (m/s^2)/PKE (m/s^2)	0.186	4.607

A.25 Worldwide WLTC Class 3-2

Representative of vehicles in Europe and Japan, WLTC Class 3-2 corresponds to vehicles with power to mass ratio greater than 34 W/kg, and maximum speed higher than 120 km/h (Fig. A.25 and Table A.25).

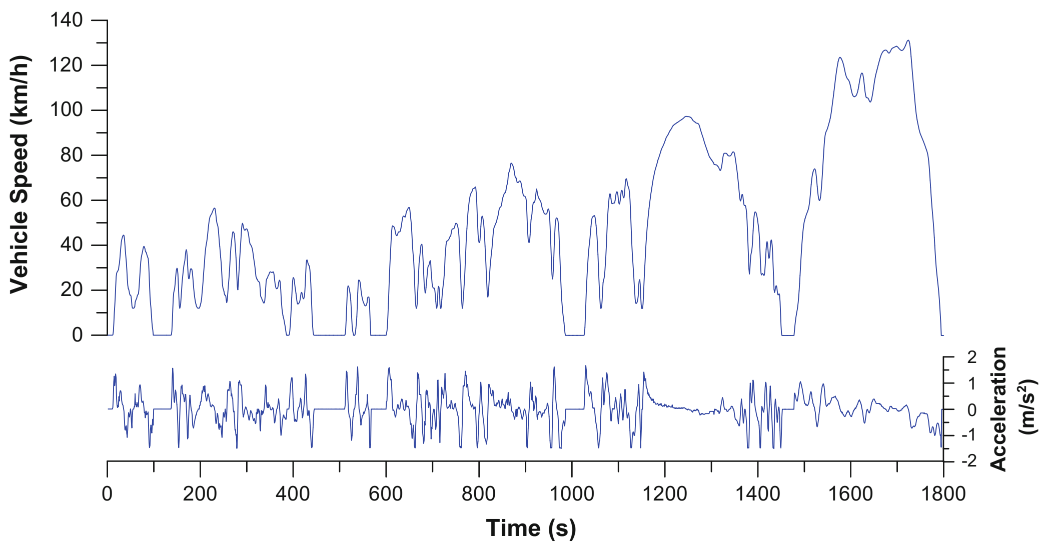


Fig. A.25 Vehicle speed and acceleration versus time of the WLTC Class 3-2

Table A.25 Technical specifications of the WLTC Class 3-2

Distance (m)/Duration (s or min)	23,266.3	1800 (30)
Maximum/Average vehicle speed (km/h)	131.30	46.53
Average driving speed (km/h)/Speed σ (km/h)	53.21	36.10
Average/Maximum acceleration (m/s^2)	0.406	1.667
Average/Minimum deceleration (m/s^2)	−0.445	−1.500
Driving time (s)/(%)	1574	87.44
Driving time (%) $V \leq 30$ km/h/$30 < V \leq 60$ km/h	40.22	27.94
Driving time (%) $60 < V \leq 100$ km/h/$V > 100$ km/h	21.72	10.11
Cruising time (s)/(%)	66	3.67
Time spent accelerating (s)/(%)	789	43.83
Acceleration time (%) $0 < a \leq 1.0$ m/s^2/$a > 1.0$ m/s^2	39.83	4.00
Time spent decelerating (s)/(%)	719	39.94
Decel. time (%) $a < -1.0$ m/s^2/$-1.0 \leq a < 0$ m/s^2	5.00	34.94
Idling time (s)/(%)	226	12.56 (13.56)
No. of accelerations/Positive acceleration σ (m/s^2)	68	0.367
Accelerations per km/per min	2.92	2.27
Number of stops/Max. interm. stop duration (s)	8	66
Stops per km/Average stop duration (s)	0.344	28.25
RPA (m/s^2)/PKE (m/s^2)	0.159	3.986

Appendix C

Regulations testing

C.1 Summary of international regulations testing proposals

Table 8. Standards required for the cycle life assessment of EV batteries

Standard	1. Initial performance	2. Charge/discharge cycles	3. Periodic performance	4. Termination criteria
ISO 12405-4:2018 [34] **(HEVs and FCVs)** (system level)	a. 25 °C ± 2 °C b. standard cycle[10] c. standard discharge to 80 % SoC	a. 25 °C ± 2 °C b. discharge-rich profile (Figure 4b) c. charge-rich profile (Figure 4d) d. repeat for 22 h e. rest for 2 h f. SoC swing: 30 %-80 % SoC	a. after 7 days perform power test (1a, standard charge, 1b, pulse power, standard charge) b. measure capacity (1C) every 14 days	terminate if: a. any limits defined by the manufacturer are reached, or b. requirements in 3a cannot be fulfilled, or c. agreement between supplier and customer
IEC 62660-1:2010 [35] **(HEVs)** (cell level)	a. 25 °C ± 2 °C b. capacity[11] c. power[13] at 50 % SoC	a. 45 °C ± 2 °C b. adjust SoC to 80 % or SoC agreed between manufacturer and customer (<16-24 h) c. (discharge-rich profile) (Figure 4b) d. (charge-rich profile) (Figure 4d) e. repeat 2c-d for 22 h f. rest for 2 h g. SoC swing: 30 %-80 % SoC	a. after 7 days measure power[13]. b. measure capacity[11] every 14 days.	terminate if: a. step 2 repeated for 6 months b. capacity or power is < 80 % of initial value
ISO 12405-4:2018 [34] **(BEVs)** (system level)	a. 25 °C ± 2 °C b. standard cycle[10] c. -10 °C d. standard charge e. standard cycle[10] f. 25 °C ± 2 °C g. standard cycle[10]	a. 25 °C ± 2 °C b. dynamic discharge power profile A (Figure 4a) c. dynamic discharge power profile B (Figure 4c) d. SoC swing: 20 %-100 % SoC e. repeat for 28 days	a. after 28 days repeat tests in step 1: 1a, 1b, 1a, 1d, pulse power,1d b. every 8 weeks repeat tests in step 1: 1c, 1d, 1e, 1a, 1b, 1c, 1d, pulse power, 1a, 1b	terminate if: a. any limits defined by the manufacturer are reached, or b. requirements in 3a cannot be fulfilled, or c. agreement between supplier and customer
IEC 62660-1:2010 [35] **(BEVs)** (cell level)	a. capacity[11] b. dynamic capacity C_D[12] profile A (Figure 4a) (25 °C and 45 °C) c. power[13] (25 °C ± 2 °C) at 50 % SoC	a. 45 °C ± 2 °C b. discharge (manufacturer) c. charge (≤12 h, manufacturer) d. discharge profile A until C_D reaches 50 % ± 5 % of initial C_D (45 °C ± 2 °C) e. rest time between each step ≤4 h f. discharge profile B (discontinue test if V reaches limit) g. dynamic discharge profile A until C_D reaches 80 % ± 5 % of initial C_D (45 °C ± 2 °C) (if T reaches upper limit, extend duration of last step in profile A/discontinue test if V reaches limit) h. repeat for 28 days	a. after 28 days, repeat tests in step 1 b. C_D (25 °C ± 2 °C)	terminate if: a. step 2 and 3 is repeated 6 times, or b. any performance value is <80 % of initial value c. cell temperature reaches upper limit set by manufacturer
IEC 61982:2012 [36] (module, system level)	a. 25 °C b. energy via profile A (Figure 4a) c. repeat 10 times (1/day) (benchmark energy)	a. discharge until 80 % of its benchmark energy content (steps 1a-c) b. recharge within 1 h of step a. b. discharge within 1 h of step b.	a. after every 50 cycles determine energy	terminate if energy delivered <80 % of benchmark energy
SAE J2288:2008 [55] (module level)	a. 25 °C ± 2 °C b. C[14] [39, 41]) c. C_D [39] d. peak power [39]	a. 25 °C ± 2 °C b. C_D ([39]) c. discharge to 80 % DoD d. fully recharge e. rest time between each step ≤1-2 h (using cooling if needed) f. repeat for 28 days	a. after 28 days repeat tests in step 1	terminate if: a. the measured capacity (either static or dynamic) is < 80 % of rated capacity, or b. the peak power capability is <80 % of its rated value at 80 % DoD

[10] Standard cycle: 25 °C ± 2 °C, 1) standard discharge (1C for HEV and FCV, C/3 for BEV) 2) rest 30 min or thermal equilibration (δT≤ ± 2 °C within 1 h), 3) charge according to specifications, 4) rest 30 min.
[11] 1) Discharge at RT (25 °C ± 2 °C) at CC (BEV = 1/3 I_t, HEV = 1 I_t)
[12] C_D: dynamic capacity. Full discharge by profile A
[13] Power: charge and discharge at several current value up to I_{max} = 5 I_t for BEV, 10 I_t for HEV for 10 s pulse. P_d (W)= U(V) * I_{max} (A); U: voltage measured at the end of 10 s pulse.
[14] 1) Discharge at 25 °C at CC C/3: end of discharge voltage/temperature/other cut-off limit specified by the manufacturer, 2) fully charge according to manufacturer, 3) OCV between charge and discharge determined by the manufacturer, 4) repeat steps 1) to 3) as specified by the manufacturer or until reproducible capacity is measured (less than 2 % difference for 3 cycles *(note: description equal to that in SAE J1798 corresponds to USABC test procedures modifying the test temperature to 25 °C instead of 23 °C).*
T: temperature, C: capacity, SoC: state of charge, DOD: depth of discharge, CC: constant current.

C.2 USABC testing manual appendix A

APPENDIX A

GENERIC TEST PLAN OUTLINE

FOR

USABC BATTERY TESTING

USABC TEST PLAN NUMBER	____________ Rev. _____		________ Date
APPROVAL:	______________________________ USABC Program Manager		________ Date
APPROVAL:	______________________________ USABC Test Manager		________ Date
ACKNOWLEDGEMENT:	______________________________ Test Lab Representative		________ Date

GENERIC TEST PLAN OUTLINE FOR USABC BATTERY TESTING

1.0 **Purpose and Applicability**

This test plan defines a series of tests to characterize aspects of the performance or life cycle behavior of a battery for electric vehicle applications. These tests may be applied to single cells, battery modules, full-size battery packs or complete battery systems (all of which are referred to as batteries in this plan). It may also be used to specify testing for multiple identical batteries subjected to the same or different test regimes (see Section 5.0.)

2.0 **References**

(To be as required by manufacturer or USABC Program Manager)

3.0 **Equipment**

Power, voltage, and current capabilities for the electronic loads and power supplies are to be specified. Special test equipment required for the conduct of this test plan (if any) is specified in the individual test procedures.

4.0 **Prerequisites and Pre-Test Preparation**

In addition to any prerequisites defined in individual test procedures, the following actions shall be performed by the testing organization prior to testing a battery under control of this test plan:

4.1 The USABC identification number for the battery shall be determined and affixed to the battery (if this has not been done by the manufacturer.) (See Appendix D for numbering system.)

4.2 The battery or battery modules shall be examined to determine that damage has not occurred during shipping or handling, and that the type and configuration (e.g. number and interconnection of modules) are correct and agree with the assigned identification number.

4.3 The battery's physical dimensions and weight shall be measured. For battery packs containing multiple subunits (modules or cells) interconnected by lab personnel after receipt, the modules will be weighed individually; in other cases, the entire battery may be weighed as a unit to avoid disassembling it (see Appendix E Worksheet).

4.4 Actual power levels (kW) and capacities (kW·h or A·h) shall be established for those planned tests specified in Section 7.0 where the procedures do not specify these levels. These values should be derived from the ratings specified in Section 5.0 of this plan, based on the manufacturer’s worksheet (Appendix E) and the measured weight or other characteristics of the battery. If these are based on values other than manufacturer's ratings or a fixed percentage of the USABC Mid Term or Long Term goals, the basis shall be noted in the test plan and the battery log and subsequently reported.

5.0 **Ratings, Test Limitations and Other Test Information to be provided**

Battery ID Number ____________________________

NOTE: If more than one battery is covered by this test plan, provide table of ID numbers. If a group of otherwise identical batteries is to be subjected to different sets of performance tests, multiple copies of Tables 7.3 and 7.4 may be used.

Development/Testing Phase _____________ (Information only)

5.1 RATINGS (DISCHARGE)

NOTE: All ratings are at Beginning of Life. A worksheet summarizing information to be supplied by the manufacturer for each battery is included as Appendix E.

Rated Capacity _______________ **(Ah)**

Ampere Hour Capacity:
3-hour (C/3) rate _____ (Ah)
2-hour (C/2) rate _____ (Ah)
1-hour (C/1) rate _____ (Ah)

Rated Energy Capacity ________ (kWh at 3-hour C/3 rate)

Test Unit Peak Power (rating at 2/3 OCV and 80% DOD at beginning of life)
_______________ (W or kW) (Nominal)

Peak Discharge Power to be applied on DST or FUDS testing
__________________ (W or kW)

Maximum Allowable (Peak) Currents to be applied during Reference Performance Cycle or Peak Power Tests:
Discharge __________________ (Amperes)
Regen __________________ (Amperes)

Percent of capacity at top of charge where regen should not be applied (if applicable)
__________ (%)

5.2 TEST TERMINATION CONDITIONS (applicable to planned tests)

DISCHARGE LIMITATIONS	VALUE	UNITS
Minimum Discharge Voltage		V/cell etc. *
Discharge Temperature Limit(s)		°C
Other (e.g. Max Current etc.)		

* Specify load conditions if rate-sensitive. (If a value less than Discharge Voltage Limit is specified, the DVL will be used for the Peak Power Test. DVL will also be used for DST or FUDS tests unless a specific exemption is included in the test plan.)

END OF LIFE TEST CONDITION(S): ____
____
____

5.3 OPERATING TEMPERATURE (Initial and limits for testing)

____
____
____

5.4 CHARGING

Procedure: ____
____
____

CHARGE LIMITATIONS	VALUE	UNITS/DEFAULT
Maximum Voltage on Charge		V/cell and/or battery
Maximum Charge Temperature		°C
Maximum Charge Rate		Amperes, watts, time
Open Circuit Time After Charge		(Default 1-24 hrs)

5.5 OTHER INFORMATION (Attachments can be referenced here)

Test laboratory Readiness Review requirements: _________________________

Thermal enclosure or other battery management system handling instructions (if applicable): ____

Commissioning Instructions: ____

Battery Configuration Description: ___________________________________

6.0 Safety Concerns and Precautions

(To be included or attached as applicable.) **NOTE: any conditions requiring safety-related monitoring provisions and/or action shall be identified and described here.**

7.0 Number and Types of Tests to be Performed Under this Test Plan

7.1 TEST CONTINUATION CRITERIA

Any ratings or required test results that constitute acceptance for testing (i.e. further testing should not be performed unless these criteria are met) should be identified here or noted in the tables. Normally, the capacity of the unit must be no less than 95% of rated, as determined either during

commissioning or the C/3 constant current discharge specified in Section 7.2. ________________
____
____

7.2 CORE PERFORMANCE TESTS (REQUIRED)

NOTE: Core Performance Tests are to be performed on all test units unless specifically exempted in writing by the USABC Program Manager, in which case the reason for exemption should be documented. If an adequate charge procedure is not furnished or available, Test Procedure #11 from Table 7.4 should be performed prior to initiating the Core Performance Test series.

TEST PROCEDURE	MINIMUM REPS	OTHER INFORMATION
2. Constant Current	3	@ 3-hour discharge rate
3. Peak Power	1	Single discharge
5. Variable Power	1	Default is DST, FUDS optional
4. Constant Power	1	@ Rate required to remove 75% of energy in 1 hour (may be done for only 1 hour)

7.3 GENERAL PERFORMANCE TESTS (OPTIONAL)

TEST PROCEDURE	NO. REQ'D	OTHER INFORMATION
2. Constant Current		Default for procedure is 12 charge/discharge cycles at C/3, C/2, C/1, C/3 discharge rates
4. Constant Power		Default power values are those required to remove 75%, 50%, 25% of battery energy in one hour. (Discharge to rated capacity or termination limits)
5. Variable Power		Regime (FUDS or DST) not performed as part of Core Performance

7.4 SPECIAL PERFORMANCE TESTS (OPTIONAL)

TEST PROCEDURE	NO. REQ'D	OTHER INFORMATION
6. Partial Discharge		Specify partial DOD value (Default 50%)
7. Stand		Specify stand period (default 48 hrs midterm, 30 days long term)
8. Sustained Hill Climb		
9. Thermal Performance		Specify matrix of temperatures & discharge/charge cycles
10. Battery Vibration		Specify random or swept sine wave excitation, normal or accel
11. Charge Optimization		Specify only if charge procedure not furnished in Section 5.4
12. Fast Charge		Specify initial rate (default 2 times normal)

7.5 SAFETY/ABUSE TESTS (under development; following table is only an example)

TEST PROCEDURE	SELECTED BATTERY ID NO.	OTHER INFO
MECHANICAL		
13A. Impact (drop)		
13B. Deformation (bend)		
13C. Intrusion (spike)		
13D. Turnover		
ENVIRONMENTAL EXPOSURE		
13E. Fire		
13F. Immersion		
ELECTRICAL		
13G. Over-Charge		
13H. Short-Circuit		
13J. Reversal		

7.5 LIFE CYCLE TESTING REGIME (OPTIONAL)

TEST PROCEDURE	TEST UNIT ID No.	OTHER INFO
14A. Accelerated Aging		Use test matrix to specify one or more test regimes & accelerating factors
14B. Actual-Use Simulation		FUDS-based; specify ambient temperature regime
14D. Baseline Life Cycle		80% DOD DST discharge at nominal environmental conditions

8.0 **<u>Special Measurement Requirements</u>**

Identify or attach number/location of temperature measurements:

____
____
____

Identify or attach number/location of voltage and current measurements (other than overall):

____
____
____

Specify any special monitoring (not already identified) required to assure that abnormal battery conditions are detected:

____
____
____

9.0 **<u>Post-Test Examination and Analysis</u>**

Identify or attach requirements for post-test examination and/or any teardown and subsequent analysis after completion of testing:

____
____
____

C.3 USABC testing manual appendix B

APPENDIX B

GENERIC REPORTING

AND

DATA ACQUISITION OUTLINE

FOR

PERFORMANCE AND LIFE TESTING

OF

ELECTRIC VEHICLE BATTERIES

GENERIC REPORTING AND DATA ACQUISITION OUTLINE
FOR ELECTRIC VEHICLE BATTERY TESTING

1.0 Purpose and Applicability

This outline defines the general formats and types of information to be acquired and reported to the U. S. Advanced Battery Consortium (USABC) for both the performance and life testing of electric-vehicle batteries. Sections 2 through 6 apply to reporting requirements. Data acquisition and retention requirements are described in Section 7.

1.1 Assumptions

This outline assumes the existence of a test plan that defines the testing to be performed on (each sample of) a given battery, the rationale (purpose) for this testing, and a body of procedures that specify in detail how to conduct each type of test. The test plan and the corresponding procedures should be referenced so that detailed procedural information need not be included in the reporting of test results.

The term ‘battery’ is used generically in this outline to designate any hardware test unit of whatever size, including cells, modules, battery packs and complete battery systems.

2.0 Test Report Format and Content

The general structure of a testing report is outlined below. Some reports may not contain all the indicated sections if less than the full spectrum of tests are performed. For example, not all batteries will be subjected to performance testing, life testing and post-test analysis. Also, the reported battery descriptive information may be limited if the battery in question is one of a group of identical items being tested. If interim reports are issued during testing, it may not be appropriate to repeat some information. In the most general case, however, testing reports should contain the following types of information:

- Executive Summary (Abstract, Conclusions, Recommendations)
- Testing Objectives
- Battery Descriptive Information
- Performance Test Results
- Life Cycle Test Results
- Post-Test Teardown and Analysis Results
- Conclusions
- Recommendations
- References

Each of these categories of information is briefly summarized below; subsequent sections treat those topics requiring more detailed definition.

2.1 Executive Summary

The executive summary is a compilation (limited to 1-2 pages) of the information that would be most significant to the casual reader. It should contain an abstract as the first part and a reiteration of any conclusions or recommendations contained in the report. The abstract itself is a brief statement (typically less than 200 words) of the purpose of the work, methods, and results. It should be a stand-alone summary of what was done, the results, and any significance of the results.

2.2 Testing Objectives

A brief statement should be provided that describes the purpose(s) for which the reported testing was done. This should be agreed to with the USABC prior to the start of testing. A test plan for the battery should have been constructed to satisfy these objectives. The report should show how and to what extent these objectives are satisfied.

2.3 Battery Descriptive Information

A description of the battery or battery system that was tested is to be provided in sufficient detail to identify what was tested. This should include any general descriptive information that was not supplied by the developer or the USABC, e.g., battery weights, photographs of fabricated assemblies, etc. Additional information is provided in Section 3.

2.4 Performance Test Results. A description of test results to be reported from performance testing is provided in Section 4.

2.5 Life Cycle Test Results. A description of test results to be reported from life cycle testing is provided in Section 5.

2.6 Post-Test Teardown and Analysis Results. Results to be reported from teardown and analysis after performance or life-cycle testing are discussed in Section 6.

2.7 Conclusions

A conclusions section is to be included to summarize the significance of the reported results, with particular emphasis on (1) the degree to which testing objectives were satisfied; and (2) the extent to which the measured battery behavior approaches the USABC goals or other pre-established requirements for the technology.

2.8 Recommendations

Recommendations should be included where appropriate to convey technical judgments or opinions, suggestions for follow-on testing or problem resolution, or other information that goes beyond interpreting the test results. Recommendations should be directed specifically at battery developers, the USABC and its program managers.

2.9 References

The battery specific test plan and all procedures used in the conduct of reported testing should be referenced at the appropriate reporting stages so that these plans and procedures can be unambiguously related to the testing performed. This will permit subsequent questions about the possible influence of testing methods on test results to be addressed.

2.10 Other Information

Test reports should include adequate definition for nomenclature used in the reports, along with acronyms and abbreviations where appropriate. Nomenclature should be consistent with the USABC glossary to avoid the need for extensive definitions.

3.0 Battery Information and Description

The initial information to be reported for any battery should be a description of the battery itself, in sufficient detail to unambiguously identify the battery and any unique conditions or limitations imposed on its testing. The intent of this information is two-fold: to clearly distinguish this particular battery and its test regime from other similar ones; and to document information other than test results that was acquired by the test laboratory during testing. In general this would include the following categories of information:

- Physical Characteristics (size, weight, number & condition of cells, interconnection, breakdown of auxiliary equipment etc.)
- Chemical/Electrochemical Characteristics (include manufacturer's specifications for capacity and power, cell voltage etc.)
- System Control, Thermal Management, Operating Description
- Battery Operating/Discharge Limits
- Charging Considerations and Requirements
- Safety Considerations (if they affect testing)

Where appropriate, this information should be supplemented by photographs or diagrams of the battery system and important components.

If only a single battery of a given type is tested, this information will normally be reported along with the performance test results. Where multiple samples of the same battery design are tested, this (common) information could be compiled once and supplied to the test sponsor after review by the laboratory(ies) conducting the testing. For multiple batteries, only the information common to all batteries need be included here; for example, if different charge algorithms are required for different test batteries, these different charging requirements can be included with the performance test results for each battery.

3.1 Battery Identification

A unique identifier will be assigned for each test battery by the USABC when the battery is delivered for testing. The battery information section will tabulate this identifier along with other descriptive data, so that all reported results can be easily related back to this identifier. The method for assigning the battery identifier is detailed in Appendix D.

4.0 Performance Test Reporting

Batteries may be subjected to a wide spectrum of performance tests, ranging from the minimum core tests (presently 6 cycles) to a test sequence requiring several months. Multiple samples of a given hardware deliverable may, in many cases, be subjected to a common test regime. Hence, the extent and frequency of performance test reporting must necessarily be tailored to the length of testing and number of test units. The minimum reporting from the testing of a single test unit is described in Section 4.1. For particular batteries, this summary information will be supplemented with appropriate graphical or other data of specific interest, as outlined in Sections 4.2-4.6. Note that this supplemental information is not expected to be provided for every battery tested; instead only selected samples of a given technology will be examined (as specified in test plans) for these aspects of battery behavior.

Where justified by the extent of testing, a final full report will be published at the conclusion of testing. This report may summarize the performance of an entire group of identical batteries; in some cases it may also include subsequent life cycle test results and/or post-test analysis results. Because of the delays inherent in generating such a report, summary performance test status information is required periodically (generally monthly) for any battery where testing lasts 2 months or more.

4.1 Summary Performance Test Results

Performance test results for each battery tested should be summarized using the format shown in Table B1. This table identifies the particular test unit and lists the key information derived from each type of test specified in the test plan as results become available. Where only minimum core testing is performed, this summary table may be the only performance test reporting required. In other cases, it will be updated as testing progresses and used for periodic reporting. Where a full performance test report is prepared, the final version of this table will be appended to the report.

Where multiple identical samples of a battery are subjected to common test conditions, an overall summary of the test results for each battery in such a group should be provided to permit easy comparison of their performance. A suggested format for such an extended results summary is shown in Table B1a. This may be extended where appropriate to include multiple groups for a given technology. The suggested format for such a high-level summary is shown in Table B2.

In addition to summarizing the general performance test results, these tables provide a mechanism for showing cycle life and for noting any changes in test conditions or battery configuration that occurred during testing.

4.2 Battery Capacity

The measured capacity of the battery in ampere-hours and watt-hour or kilowatt-hours should be reported for the following test regimes if performed:

Constant Current Discharge
Constant Power Discharge
Variable Power Discharge (DST/FUDS)

These results should be representative, in that they are likely derived from multiple tests. For batteries that require time or exercise to reach a stable capacity, both the initial and the stable capacities should be reported.

4.3 Voltage-Current Behavior

Battery voltage (over time or as a V-I plot) should be reported graphically for variable power discharge cycles. This should include open circuit voltage behavior during the rest periods (if any) and after the end of discharge. Voltage-current behavior during a charge cycle should also be reported graphically. For batteries incorporating multiple modules or sub-units, a graphical representation of the voltage variations between modules should be reported for one or more constant current or constant power tests.

Table B1. Summary Test Results

HARDWARE CHARACTERIZATION SUMMARY

USABC ID: _____________ REPORTING DATE: _____________ Weight (kg): _________
START DATE: _____________ COMPLETION DATE: ____________ Volume (L): _________
(* CORE TESTS) Basis: _______________

PROCEDURE#	DESCRIPTION	RESULTS	COMMENTS
2 (part)	C/3 Capacity Verification	____ Ah _____Wh	
2 12	Charge/Dischg Effic: (Coul) (Energy) Fast Charge	_______ % Ah _______ % Wh __ % Ah ___% Wh	(Describe Charge Method)
2	* Constant Current @ C/3 Constant Current @ C/2 Constant Current @ C/1	___ Ah ____ Wh ___ Ah ____ Wh Ah Wh	
4	* Constant Power @ ____ W Constant Power @ ____ W Constant Power @ ____ W	___ Ah ___ Wh ___ Ah ___ Wh Ah Wh	(Highest value [CORE TEST] should be that required to remove 75% of battery energy in 1 hour)
5	* Variable Power w/DST or FUDS	____/_____ Wh net/gross ____/_____ Ah net/gross	(For DST, report Wh & Ah at unreduced and reduced power conditions, and any procedure deviations)
3	* Derived Peak Power (30s at 80% DOD)	_____ W	(Note the rated peak power if significantly different than the derived value.)
7	Stand time ___h	% Loss	
8	Hill Climb (6 minutes)	Max. % DOD	
6	Partial Discharge	% Loss	
14	Life (DST) Status (cycling start date _____)	__ Cycles total __ Cycles DST	(Also report most recent Reference Performance Tests: capacity on DST, 80% DOD power on Peak Power)

Note: for multiple identical deliverables, this table may be extended with additional Results columns. See Table B1a for example.

Table B1a
Summary Test Results (Extended for Multiple Test Units)

Report Date: ____________________ USABC Number(s) ____________________________

Procedure	Description	Units	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
1	Mass Volume	kg l										
2 (part)	C/3 Capacity	Ah Wh/kg Wh/l										
2 (part)	Efficiency	% Ah % Wh										
12	Fast Charge	% Acceptance										
2	CC @ C_3/3 CC @ C_2/2 CC @ C_1/1	Ah Ah Ah										
4	CP @ E_3/3 CP @ E_2/2 CP @ E_1/1	Wh/kg Wh/kg Wh/kg										
5	Variable Power DST	Wh/kg Wh/l										
3	Peak Power 30s @ 80% DOD	W/kg W/l										
7	Stand Test 1h 48h 168	 % Loss % Loss % Loss										
8	Hill Climb (6m)	Max. % DOD										
6	Partial DOD Cycles to Full	% Loss Cycles										
14	Life: Peak Pwr 3h Rate DST	Cycles Cycles Cycles										
	Test Plan (Brief Description)											

Note: Comments on Table B1 should be observed for this summary test results table also.

Table B2
Summary Test Results (Multiple Groups of Identical Test Articles)

Report Date: __________

PERFORMANCE AND STATUS SUMMARY OF ________________________________ CELLS/MODULES/BATTERIES UNDER TEST AT ________									
Identification Number	Weight kg	Volume L	Specific Energy C/3 Initial Ah Wh/kg	Present Ah Wh/kg	Net Specific Energy DST Initial Ah Wh/kg	Present Ah Wh/kg	Peak Power @ 80% DOD, W/kg Initial	Present	Total & DST Cycles Accrued As of___

NOTE: Weights or volumes used for calculating normalized performance values (e.g. Wh/kg, Wh/l, W/kg) should be the actual measured values of the units under test; otherwise a clearly defined basis for these values must be provided.

4.4 Other Observations

Observed battery behavior that could significantly affect the interpretation or understanding of test results should be noted in narrative fashion. This may include, for example, deviations from procedures due to equipment or battery limitations, or test anomalies which are outside the expected range of results. Also reliability or maintenance concerns that might affect the suitability of the battery for life cycle testing should be reported.

5.0 Life Cycle Test Reporting

Summary status tables (e.g., Tables B1 and B2) are to be used as the basic means of reporting accumulated cycles and degree of performance degradation during life cycle testing. This status report (with accompanying pertinent graphical data) will be provided throughout the lifetime of the unit under test at periodic intervals. This reporting will act as a supplement to the summary reports provided during performance characterization. The final report will summarize the life cycle history of the test unit (or an entire group of identical batteries where appropriate.)

5.1 Life Cycle Tests

For any selected life-cycle testing regime, the initial test(s) should be reported in the same level of detail as the comparable (variable power discharge) performance test. Reporting for subsequent tests should be confined to a small number of selected parameter values, preferably as specified in the test plan. For example, if a life cycle discharge is to be terminated after a fixed number of Ah is removed from the battery, the voltage at end of discharge should be reported; conversely, if the test is terminated on a predetermined voltage limit, the battery capacity should be reported. A graphical representation of the selected parameters versus (cumulative) cycle count should be provided.

5.2 Frequency of Reporting

Because life-cycle tests on a given battery may require months or years to complete, the reporting of such results should take place on a periodic basis to provide timely status information to the test sponsor. Initial life cycle test results will be reported in accordance with the test plan (e.g., after the second RPT set is performed). Subsequent status updates would then be provided at agreed-on intervals (e.g. monthly or quarterly) depending on the expected duration of the testing.

Note: additional guidance for periodic reporting of test results (e.g. quarterly and/or weekly) is under development and will be provided in a future revision to this manual.

6.0 Post-Test Teardown and Analysis Reporting

Detailed procedures for post-test teardown and analysis have not yet been defined. Presumably, the results of such analyses would be reported as photographic/microphotographic records, chemical analysis values, and narrative information. Requirements for such analysis (and resulting reporting) should be specified in the test plan for each test unit.

7.0 Data Acquisition and Retention Requirements

7.1 Measurement Parameters

The basic requirement of the data acquisition system is to sample battery parameters in a manner that assures that the test unit response to load demand can be accurately measured and/or reproduced.

All battery discharge/charge cycling requires three fundamental measurements: voltage, current, and temperature. Measurement to be performed during vibration testing are described separately in Procedure #10. The time that each parameter is sampled is recorded with the measurement. For laboratory charge/ discharge testing, it is generally adequate to derive battery power from the multiplication of current and voltage. However, if more than 1 millisecond elapses between any voltage and current samples used to derive power, a power measurement instrument must be used to acquire battery power information.

Data acquired from these measurements is used to derive the remaining battery discharge/charge parameters such as cell/module/battery resistance, capacity (ampere-hours), and energy (watt-hours).

7.2 Test Modes and Data Sampling Requirements

The modes in which electrical testing may be performed on a battery are as follows:

Constant Current Discharge	(CC)	
Constant Power Discharge	(CP)	
Variable Power Discharge	(VP)	FUDS, DST
Peak Power Discharge	(PP)	(is a Variable Current Discharge)
Recharge	(RCG)	(CC and/or CP)

These tests modes have varying sample requirements. Recharge, Constant Current Discharge, and Constant Power Discharge testing require a minimum of one sample (a) every 10 minutes or (b) whenever any measurement changes by more than 2% of its previous value (of current, voltage or temperature) to be recorded during the full duration of a test.

Variable Power or Peak Power discharge tests require sampling of all measurements at a minimum of one sample per second during periods of current or power changes. Acquisition systems capable of programmable sampling may be set up to reduce the amount of data storage by decreasing sampling during static portions of tests (e.g. the constant current periods during a Peak Power Test.) If sample rates for slowly moving parameters such as temperature can be programmed independently, further reduction in the amount of stored data may be effected by decreasing the number of samples (per channel) for such parameters to the same as those required for RCG, CC or CP tests.

Sampling requirements for Life Cycle DST discharges (Procedure #5A) may be reduced by the following two-step process: (a) sampling test unit voltage and current (only) near the beginning and end of each power step in a DST profile; and (b) sampling all measurements near the end of the maximum discharge (100%) and maximum regen (50%) steps for each 360 second DST profile completed.

7.3 Measurement Accuracies

Required accuracies for the respective measurements are:

Measurement	Accuracy (% of Reading except as noted)
Voltage	< 1.0
Current	< 1.0
External Temp	+/- 3°C
Internal Temp	+/- 3°C
Ambient Temp	+/- 3°C
Power	< 3.0
Vibration (Accel)	< 4.0

The implied accuracy for other derived (calculated) data such as accumulated energy or Ah capacity is data system dependent but generally should not exceed 3%.

7.4 Data Retention

For each discharge/charge cycle during both performance and life cycle testing, a tabulation of summary data, including cycle number, test duration, calculated values (e.g., energy and capacity), and starting and ending values for parameters such as open circuit voltage and temperature, will be permanently retained.

For the characterization performance tests and the Reference Performance Tests during life cycle testing, the minimum number of samples identified in Section 7.2 should be retained permanently for each discharge/charge cycle.

For life cycle testing, the recorded data identified in Section 7.2 must be retained a minimum of 2 months, after which it can be deleted (except for summary results) with the written consent of the program manager. Any summary results that must be retained for each life cycle should be identified in the test plan.

7.5 Data Formats

Test results and other data may be retained in at least 4 formats as appropriate: narrative, numerical/tabular, graphical, and computer files. All data to be retained should be stored in permanent, secure, and backed-up computer files. For graphs having relatively few data points, the values should also be retained and reported in numerical/tabular form for subsequent analysis use.

C.4 USABC testing manual appendix G

APPENDIX G

USABC CRITERIA
FOR ADVANCED BATTERY TECHNOLOGIES

USABC Primary Criteria for Advanced Battery Technologies

Parameter	**Mid Term**	**Long Term**	**Test Proc #**	**Test Unit Type***
Power Density W/L	250	600	3	C,M,P
Specific Power (Discharge) W/kg (80% DOD/30 sec)	150 (200 desired)	400	3	C,M,P
Specific Power (Regen) W/kg (20% DOD/10 sec)	75	200	12	C,M,P
Energy Density W·h/L (C/3 Discharge Rate)	135	300	2,5B	C,M,P
Specific Energy W·h/kg (C/3 Discharge Rate)	80 (100 desired)	200	2,5B	C,M,P
Life (Years)	5	10	Correlate from 14	C,M,P
Cycle Life (Cycles) (80% DOD)	600	1,000	14	C,M,P
Power & Capacity Degradation (% of rated spec)	20%	20%	14C	C,M,P
Ultimate Price ($/kW·h) (10,000 units @ 40 kW·h)	<$150	<$100	---	---
Operating Environment	- 30 to 65°C	-40 to 85°C	9	C,M,P
Normal Recharge Time	<6 hours	3 to 6 hours	11	C,M,P
Fast Recharge Time	40-80% SOC in <15 minutes	40-80% SOC in <15 minutes	12	C,M,P
Continuous Discharge in 1 hour (no Failure)	75% (of rated energy capacity)	75% (of rated energy capacity)	4	C,M,P

* C = cell, M = module, P = pack

USABC Secondary Criteria for Advanced Battery Technologies

Parameter	**Mid Term**	**Long Term**	**Test Proc #**	**Unit Type***
Efficiency (C/3 discharge 6 hour charge)	75%	80%	2	C
Self-Discharge	<15% in 48 hours	<15% per month	7	C
Maintenance	No Maintenance (service by qualified personnel only)	No Maintenance (service by qualified personnel only)	---	---
Thermal Loss (for high temperature batteries)	3.2 W/kWh 15% of capacity 48-hour period	3.2 W/kWh 15% of capacity 48-hour period	7	P
Abuse Resistance	Tolerant (minimized by on-board controls)	Tolerant (minimized by on-board controls)	13	P
OTHER CRITERIA				
Recyclability - 100%				
Packaging Constraints				
Environmental Compliance (manufacturing process, transport, in use and recycling)				
Reliability (tie to Warranty and cycle life)				
Safety			13	C,P
Vibration Tolerance			10	C,P

* C = cell, M = module, P = pack

C.5 USABC testing manual appendix H

APPENDIX H

PROCEDURE TO MEASURE ACTUAL PEAK POWER

APPENDIX H

Procedure to Measure Actual Peak Power

Purpose:

The purpose of this test is to measure the actual capability of a battery to deliver sustained power for 30 second intervals at one or more depths-of-discharge (DODs). It should be noted that this test will load the battery with discharge currents that will depress its voltage to 2/3 or less of the open circuit value. Depending on the battery design, this may require extremely high currents and may be damaging to the battery. A more detailed procedure for the conduct of this test can be obtained on request from the Idaho National Engineering Laboratory.

Abstract:

Charge the battery, allow it to stand for one hour at open circuit, and discharge it to the intended DOD at a constant current of $C_3/3$ amperes. Interrupt the $C_3/3$ discharge and determine the open circuit voltage (OCV) at this DOD. Sweep the discharge current (in approximately 5 seconds or less) to a value that reduces the battery terminal voltage to less than 2/3 of its open circuit value at this DOD; then immediately return the discharge current to zero at the same sweep rate. From a graph of the voltage vs current during the (increasing) sweep, determine the current corresponding to 2/3 OCV at the given DOD; this current will be used as the test current for the subsequent peak power test. The $C_3/3$ discharge can be continued and additional sweeps made at other DODs to determine the appropriate test currents for these DODs.

Recharge the battery, wait one hour at open circuit, and discharge the battery to the intended DOD at $C_3/3$. Then discharge the battery at the previously determined test current for 30 seconds while recording voltage as a function of time. The peak power available from the battery is defined as the product of the 30 second sustained current and the time-averaged voltage over the 30 second discharge step. This $C_3/3$ discharge can also be continued to other DODs and additional 30 second discharges can be done using the test current previously determined for each DOD.

This test should normally be repeated at least once, i.e. performed a total of two or more times.

Data Acquisition and Reporting Requirements:

Data to be acquired includes battery ampere-hours to each DOD at which testing is conducted, battery temperature at each DOD, voltage as a function of current at each of the initial sweeps, and voltage as a function of time during each of the 30 second discharge steps. Additional summary information to be reported should include a plot of peak power vs depth of discharge.

C.6 USABC testing manual appendix I

APPENDIX I

DERIVATION OF
USABC BATTERY PEAK POWER CALCULATIONS

Appendix I

Derivation of USABC Battery Peak Power Calculations

Model

A battery is assumed to be representable as shown in Figure 1, as an ideal battery with a series resistance R. Discharge current is considered to have a negative sign, i.e. current into the battery is positive. This is a common although not universal convention among battery testing laboratories, and it has been adopted as the standard for USABC testing to assure consistency. This convention means that **all** discharge quantities (power, energy, capacity etc.) will be algebraically **negative**. This may seem counterintuitive, but in fact the common understanding of "discharge power" and "charge/regen power" is that these are "sign less" quantities where only their magnitude is of interest; the fact that they have opposite signs is expressed in the "discharge" and "charge" labels.

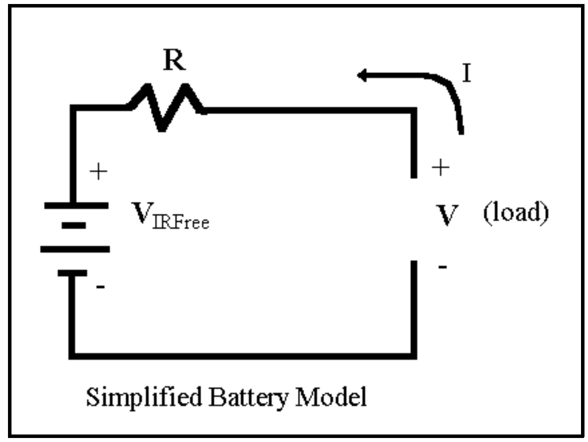


Figure 1

Resistance

For purposes of estimating peak (discharge) power capability at a given depth of discharge, a 'dynamic' resistance is determined based on a measurement of ΔV/ΔI between a base current and a high current step. The changes in voltage and current are measured from a point in time just before the beginning of a 30 second current pulse to a point near the end of the 30 second pulse, as shown in Figure 2. The resulting resistance value is calculated as:

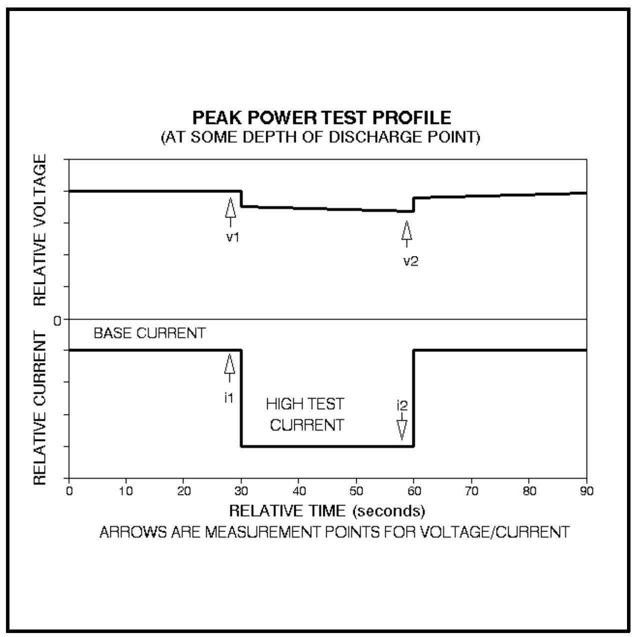


Figure 2

$$R = \Delta V / \Delta I = (V_1 - V_2) / (I_1 - I_2)$$

The numeric value of R is always positive because the value of I (by convention) is negative.

Ir_{free} Voltage

An estimate of open circuit voltage, called 'IR_{free} Voltage', is derived by extrapolating the resistance (i.e. the $\Delta V/\Delta I$ behavior) back to zero current at the pulse test conditions:

$$V_{IRFree} = V - IR$$

where either V,I pair (V_1, I_1) or (V_2, I_2) can be used for the calculation. The sign of the IR term must be negative, again because current out of the battery has a negative sign.

Peak Power Capability

By USABC convention, peak power is the maximum discharge power which a battery can produce into a load for 30 seconds (at a given depth of discharge) without allowing the voltage to drop below 2/3 of its open circuit value (OCV) at that DOD. The discharge voltage is also restricted to be above a Discharge Voltage Limit (DVL), which is determined as the higher of (a) 2/3 of OCV at 80% DOD at beginning of life or (b) the manufacturer specified minimum discharge voltage. Limiting the voltage under load to 2/3 OCV or the DVL is done for efficiency and propulsion system design considerations. This means the resulting battery peak power capability is less than the theoretical maximum, which would occur for a load that depressed the voltage to ½ OCV. The USABC peak power capability is **calculated** (not measured) based on the voltage and current deliverable to the load as follows:

$$Power_{load} = Voltage_{load} * Current_{load}$$

For the USABC peak power conditions, using the resistance and IR_{free} voltage,

$$Voltage_{load} = 2/3 * V_{IRFree}$$
$$Current_{load} = - (1/3 * V_{IRFree}) / R$$

$$\text{Peak Power Capability} = (- 2/9) * (V_{IRFree}^{2}) / R \qquad (1)$$

Because the OCV (at depths of discharge greater than 80% or late in life) may sometimes be less than the value at 80% DOD at beginning-of-life, it is also necessary to determine the power which may be delivered without dropping below the Discharge Voltage Limit (DVL). If this value is less than that calculated in equation (1), it becomes the Peak Power Capability instead. Without this restriction, the power calculated in (1) might be obtainable only at an unusably low voltage. This calculation is:

$$Voltage_{load} = DVL$$
$$Current_{load} = - (V_{IRFree} - DVL) / R$$

$$\text{Peak Power Capability} = - DVL * (V_{IRFree} - DVL) / R \qquad (2)$$

An additional constraint is placed on the calculated peak power capability by requiring that it must not be a value that would exceed the manufacturer's Maximum Rated Current for the battery. An alternative value based on this Maximum Rated Current, I_{MAX}, is calculated as:

$$\text{Peak Power Capability} = I_{MAX} * (V_{IRFree} + R*I_{MAX}) \qquad (3)$$

The V + RI term in this equation is the estimated load voltage at I_{MAX}, because V_{IRFree} is the "effective" open circuit voltage at the given depth of discharge.

As a final constraint, if voltage or current limiting is encountered during a given step, this means that the battery is not capable of sustaining the test current for 30 seconds at this depth-of-discharge without exceeding either I_{MAX} or its minimum voltage. In this case, the actual power measured at the end of the step is reported as the Peak Power Capability. The actual 30 second sustained power achievable at this point may be slightly larger than this value (because the step may have started at a higher power), but the exact value cannot be determined without additional tests; hence this value is **defined** as the Peak Power Capability under these conditions.

The most restrictive value resulting from equations (1), (2) or (3) is reported as the Peak Power Capability unless voltage or current limiting occurs. Note that equations (1) and (2) are equivalent at 80% DOD at beginning of life, and equation (3) only applies if the manufacturer has chosen to restrict the maximum discharge current.

Base Discharge Rate

The base discharge rate is chosen as a current which will make the average discharge current for the entire test equal to the C/3 discharge rate. This can be calculated by setting the coulombs (i.e. ampere-seconds) of charge removed in a complete C/3 discharge (lasting 3 hours, or 10,800 seconds) equal to that removed by the combined Base Discharge and High Test Current portions of the Peak Power Test presuming it lasts for 3 hours total also as follows:

$$\text{(coulombs in C/3 discharge)} = \text{(coulombs in Peak Power discharge)}$$

$$(C_{rated} \div 3) \bullet 10800 = I_{base\ discharge} \bullet (10800-300) + (I_{high\ test\ current} \bullet 300)$$

C_{rated} is the ampere-hour capacity, and ($C_{rated} \div 3$) is the 3-hour discharge current. Thus the units on both sides of this equation are ampere-seconds. Note that the total duration of the ten high current steps in a peak power test is 300s, leaving 10,500s for the base discharge portion of the test. Solving this equation for $I_{base\ discharge}$ gives the equation in the procedure:

$$I_{base\ discharge} = (12 \bullet C_{rated} - I_{high\ test\ current}) \div 35$$

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