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ZEBRA®battery integration in "Th!nk *City*" pure battery electric vehicle

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Abstract

TH!NK *City* is a modern urban electric car. Also powered by ZEBRA®battery with zero emissions and high energy efficiency, it can cover up to 180km with one charge and a maximum speed of 100km/h.

THINK from Oslo Norway and MES-DEA SA from Stabio Switzerland worked together on this project for years developing a new concept of TH!NK *City* electric vehicle.

This article explains the work done by these companies to integrate the ZEBRA®battery into the TH!NK *City* vehicle. Starting from the study of the right battery installation, subsequently analyzing in detail all the main system requirements and devices specifications to achieve the correct integration. In particular it describes the working of the ZEBRA®Battery Management Interface software after all the changes done to comply with the Power Control Unit requirements.

Keywords: battery, EV, BMI, sodium-nickel-chloride-battery, ZEV.

1 Introduction

TH!NK *City* vehicle is a "plug in" electric vehicle, emission free and 95 percent recyclable. It works with different energy storage solutions; one of these is ZEBRA®battery with a specific energy of 120Wh/kg, a power of 150 W/kg and a nominal energy of about 28.2KWh.

Drawing on 17 years of experience in electric vehicle development and production, THINK is not a typical car industry start-up. The first prototype predecessor to today's modern TH!NK *City* was developed in 1991.

The production facilities of THINK is located at Aurskog, some 50km east of Oslo. The first electric vehicle production line was installed here in 1998. TH!NK *City* was put in serial production in 1999, supported by American car giant Ford. During this period THINK started to work with MES-DEA SA using the first ZEBRA® batteries on their vehicles.

In 2006, Norwegian investors bought THINK and an experienced management team entered the scene. During last years the process has moved from producing prototype cars to complete production cars using ZEBRA®batteries and the relationship between these two companies has become very strong thanks to the high level of reliability and performance reached from the ZEBRA®battery technology.

A further share issue during 2007 has prepared THINK to go into regular serial production of the 5th generation TH!NK *City*. Present capacity at Aurskog is an annual of 5,000 units per shift.

TH!NK *City* consists of 570 bought-in components, shipped from suppliers in Europe, Asia and the US. THINK manages the global part supply logistics and carries out the final assembly, testing, validation and quality control sign-off of all vehicles.

One of the major supplier of THINK (especially for ZEBRA®battery) is MES-DEA SA that is a company devoted to development, production and marketing of components for electric vehicles. Its mother company, MES has produced components for the automotive industry as well as for the domestic appliances industries for many years.

MES-DEA SA has been a division of MES SA for some years. With the acquisition of the ZEBRA® battery technology in 1999 MES-DEA SA was founded as an independent company.

The ZEBRA® project was initiated in South Africa and developed in England and Germany. Today ZEBRA®batteries are produced by MES-DEA SA, with a 20.000 m² production plant located in southern Switzerland, bordering Italy.

MES and MES-DEA are now part of a Team of 14 companies working in developing, designing, producing and commercialising components for Automotive and Household Industries with 3’800 employees and 220’000m2 of working facility.

By the end of 2008 already 500 ZEBRA®batteries has been delivered to THINK.

2 The mission

The mission of THINK and MES-DEA is to create the most environmentally friendly vehicles in the world in a commercially successful way.

Concern for the environment has been at the heart of the development of TH!NK *City*, the car itself is designed to be completely recycled**.**

The vision is to provide carefree, carbon-free mobility, a better way of moving with the same level of safety and comfort as any conventional vehicle.

In a TH!NK *City* car 90% of the ZEBRA® battery energy available is channelled directly into using the vehicle. Its energy efficiency is three times higher than a car with an internal combustion engine. Using a TH!NK *City* vehicle, it is possible to drive three times the distance for the same amount of energy. Furthermore there is the big benefit of low operating and maintenance costs, because electric motors don’t have many moving parts that require servicing. TH!NK *City* and other EVs attract substantial government incentives in most European markets. This includes incentives like 6-8000€ in cash support and exemption from road tax, parking fees and the London congestion charge. The customer should only pay a monthly fee that works out less than you would have to pay at a petrol station. A comprehensive and well-established safety concept makes TH!NK *City* a very safe car, homologated for European markets.

3 The vehicle

TH!NK *City* vehicle is safe and easy to drive offering driving features with high performance, zero local emissions and high energy efficiency. With ZEBRA® battery, the vehicle is able to travel up to 180 kilometres (110miles) in one charge, with a top speed of 100km/h (65 miles/h). The ZEBRA®battery can be charged through an ordinary plug, taking a time of about eight hours for 80 per cent charge. The managements of THINK and MES-DEA companies consider safety and reliability as important factors. For this reason the car is equipped with ABS brakes, airbags and three-point safety belts with pretensions. The frame and doors are designed to absorb energy and distribute it away from the passenger cell.

Figure1: TH!NK *City* vehicle

The following tables contain the main specifications and features of TH!NK *City* car.

Top speed	100Km/h
Acceleration	0-50Km/h in 6.5seconds
Acceleration	0-80Km/h in 16.0 seconds
Range IEC**	170Km (summer tires, heater off)
Range FUDS*	180Km (summer tires, heater off)
Range UDC***	203Km
Typ. Charge time	0-100%(state of charge) - 13h approx.
230VAC/14A	0-80%(state of charge) - 9.5h approx.
*American std for calculating range of EV	
** European std for calculating range of EV	
*** Range during city driving only	

Figure 2: TH!NK *City* specifications

Number of seats	2 (2 rear seats as an optional extra)
Number of doors	3 including rear hatch
Lenght	3120mm
Width	1604mm
Height	1548mm
Turning radius	4.5m
Net car weight	1113Kg
Total weight	1397Kg
Load capacity	284Kg

Figure 3: TH!NK *City* features

The majority of faults and warning conditions related to the electric propulsion or ZEBRA®battery system are logged and can be reviewed with THINK and MES-DEA diagnostic tools especially designed and reviewed for this purpose. This has significantly simplified fault tracing activities.
The vehicle instrument cluster has been designed to let the driver easily understand all the information available on the vehicle dashboard especially in case of important warnings.

Figure 4: TH!NK *City* cluster instrument

3.1 Vehicle dashboard indicators

All the vehicle indicators and commands on the dashboard were studied and designed to inform the driver on the system operational status. Much of which the battery itself has a considerable influence.

3.1.1 CSOC Display

The PCU continuously transmits the customer state of charge (CSOC) to the Instrument Cluster via the SOC output. The PCU calculates the CSOC based on the battery state of charge (BSOC) provided by BMI via CAN bus.
There is also a Low SOC Indicator used to notify the driver that remaining available energy is approaching 0.

3.1.2 Charging Indicator

When the PCU operating state is Charge and the charger is enabled, the PCU enables the Charging Indicator output. When End Of Charge = True, the PCU disables the Charging Indicator output. When the PCU operating state is Ready, the PCU pulses the Charging Indicator output at a frequency of 0.5 Hz and a 50% duty cycle.

3.1.3 Power Limit Indicator

The Power Limit Indicator is used to indicate that available power is limited due to battery or PCU operational status.

3.1.4 Overtemp Indicator

The Overtemp indicator is lit if the temperatures of the battery, PCU or Motor is approaching operational limits.

3.1.5 Malfunction Indicator Lamp (MIL)

If a fault should occur the malfunction indicator lamp is lit. When the PCU detects any malfunction, it enables the MIL Lamp output.

3.1.6 Battery current indicator

On the dashboard the battery current provided by the BMI is displayed to the driver. There are further several indicators that are not related to the battery itself, but to the rest of the vehicle system(s), used to indicate system information to the user. ABS warning Indicator, Brake fault indicator, 12 V Battery Indicator Gear position Indicators

4 The system design

MES-DEA engineers in collaboration with THINK team spent a long time working to achieve the actual system configuration.
The car was designed in the same way that the grand masters of Functionalism designed homes; by starting from the bare essentials. From that starting point, the car has been developed as a modular system. This makes TH!NK *City* a vehicle designed not only for present-day electric vehicle technology, but also for future innovative solutions.
The whole system was designed in order to match ZEBRA®batteries specification with vehicle performance.
Batteries system capacity was defined in order to satisfy the complete vehicle specification in all the possible operative conditions maintaining in the meantime an acceptable long life of the battery.
The vehicle has really low energy consumption in particularly during urban city driving it is about 138.9Wh/km (especially in summer time when the energy consumption is lower than other seasons: lights, heating, windscreen wiper, winter tires).
Special tests have been done by MES-DEA to define the right energy available at different discharge rate and as reported in the graph below the energy is quite constant with discharge rate higher than 2hours.

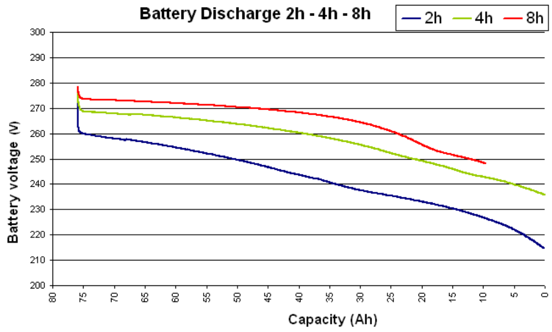

Figure 5: Z5 battery discharge energy curves

The ZEBRA®battery on this vehicle should be managed according to the general recommendations of:

- Regularly reaching the end of charge condition.
- Avoid regular deep discharge, below 20% SOC.
- Maximum discharge rate of 2 hours.

The first point of the system design was to decide where to install exactly all the different devices and especially the ZEBRA®Battery.
After the battery installation and connection it was necessary to analyze and modify the standard BMI software to achieve the PCU specifications and vehicle requirements.

4.1 ZEBRA®Battery installation

TH!NK *City* electric vehicle has been designed with MES-DEA help around the ZEBRA®battery cassette located in the middle of the car, underneath the seats. Here, the module is well protected and ideally placed from a safety point of view. This gives a good distribution of weights between the front and rear axel, and provides the vehicle with a very low centre of gravity. The ZEBRA®battery tray is covered by different special thermal insulation layers to protect the vehicle inside, from further battery overheating that could happen for instance in case of car accident. Thermal insulation is placed on top of the Z36 battery in two layers.

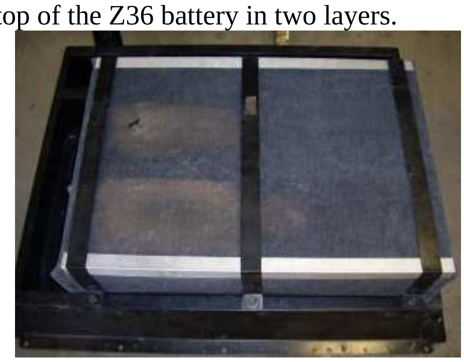

Figure 6: Battery thermal insulation layers

The lower layer is in close contact with the battery and the upper is in close contact with the battery retention straps. Protection angles, one to the front and one to the rear, are placed on top of this upper layer to protect the insulation material and the battery casing from pressure from the retention straps. Thermal insulation is fastened to the lower side of the seat deck in order to add further protection.
Tests have been done to verify the installation, simulating a battery overheating (temperature of 600°C) on its external chassis.
During these tests the temperature were logged at various locations in the vehicle:

- Sensor 1: Top of battery case (blue).
- Sensor 2: Seat deck top (pink).
- Sensor 3: Bottom of centre console (Red).
- Sensor 4: Bottom of internal sill protection (Brown).
- Sensor 5: Inside lower part of stuffing in seat (green).

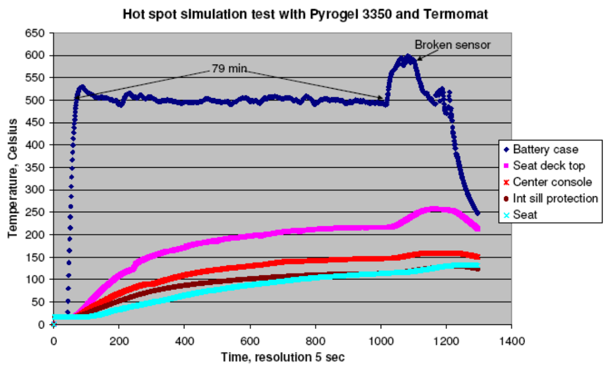

Figure 7: Vehicle Temperature profile

As shown in the picture above, the test result determines that temperature values do not reach hazardous levels in the vehicle.
Also crash test performed on vehicle with fully charged ZEBRA®battery prove the system safety.

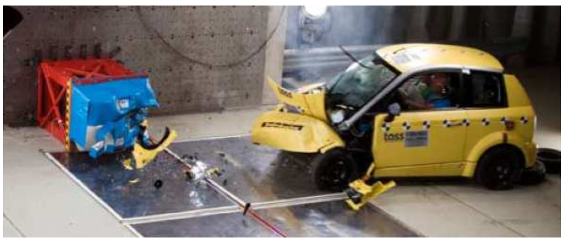

Figure 8: Crash test

ZEBRA®batteries have been also tested by MES-DEA under penetration, water immersion and fire presence and even in these cases no hazardous situations occurred.

4.2 The system operation and its main parts

As reported in the picture below, the motor receives power from the traction ZEBRA®battery. The ZEBRA®battery with its BMI is connected to the PCU and to the vehicle CAN bus .
PCU manages much of the vehicle and battery functionality over the CAN bus.

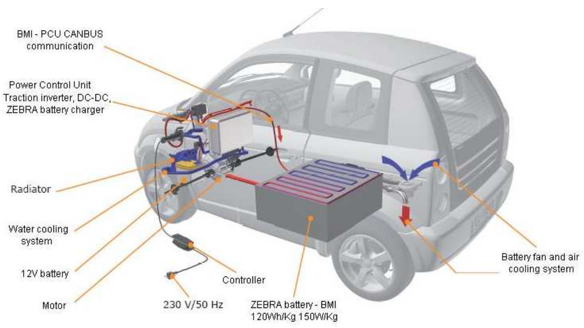

Figure 9: TH!NK *City* system

The BMI supervises the battery operation, monitoring all the main parameters like current, terminal voltage, temperature, state of charge, insulation resistance between main circuit and battery chassis. As shown in the picture below the main parts of the vehicle are the PCU the BMI/ZEBRA®battery and the electric motor.

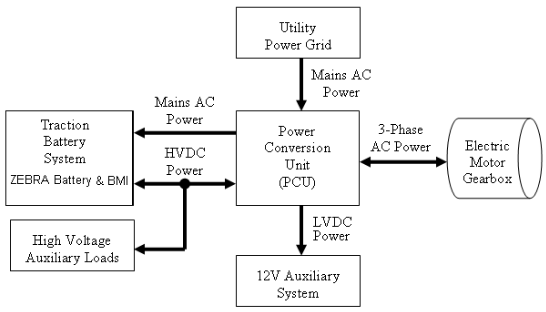

Figure 10: Block diagram

4.2.1 The PCU

Figure 11: The PCU

The PCU controls the vehicle propulsion system of the TH!NK *City* electric vehicle.
It consists of three modules that are contained in a common enclosure: Traction Inverter Module (TIM), DC/DC Converter Module (DCM), and Traction Battery Charger Module (TBCM).
The PCU distributes power to the drive system and other vehicle systems as well as sending power back to the battery from the regenerative braking system (when the gas pedal is released or when the brake pedal is used).
The motor controller makes sure that the vehicle consumes energy in an efficient manner.
The primary functions of the PCU are to:

- Convert the high voltage DC (HVDC) traction ZEBRA®battery power to 3-phase AC power to precisely drive the power train traction induction motor for high bandwidth, high efficiency, and low ripple torque control.
- Convert of 3-phase AC power from the AC induction motor to HVDC power to recharge the battery pack during regenerative braking for energy recovery purposes.
- Convert of high voltage from the traction batteries to low voltage (DCM) to provide power for low voltage loads and for charging the auxiliary 12V battery.
- Convert of mains AC power to HVDC power for charging the ZEBRA®battery in the vehicle and powering auxiliary loads. This built-in battery charger (TBCM) converts alternating current from the grid to direct current that charges the ZEBRA®battery in an optimal manner.
- Distribute of HVDC power from the battery pack to the fluid heater and air conditioning systems.
- Distribute of mains AC power to the BMI to provide power for the AC heater in the battery pack.

In all PCU operating states, the PCU monitors the CAN bus for periodic messages from the BMI.
The PCU and the electric motor are fluid cooled.
The PCU software is responsible for thermal management of these devices. It controls the MES-DEA cooling pumps and the radiator fan to keep temperatures of the PCU and electric motor within operating limits.
In all the working conditions the PCU manages the system to respect the ZEBRA®battery limits sent by the BMI via CAN bus. To ensure battery and vehicle operation, BMI CAN bus messages are closely monitored.

In discharge the PCU limits the total torque request to respect the following limits:

- Voltage Min (for peak power).
- Voltage Max (for regenerative mode).
- Current Max discharge (for peak power).
- Current Max charge (for regenerative mode).

In charge the PCU limits the charger power to respect the following limits (also according to the BMI command):

- Voltage Min.
- Voltage Max.
- Current Max discharge.
- Current Max charge.

4.2.2 The BMI/ZEBRA®battery

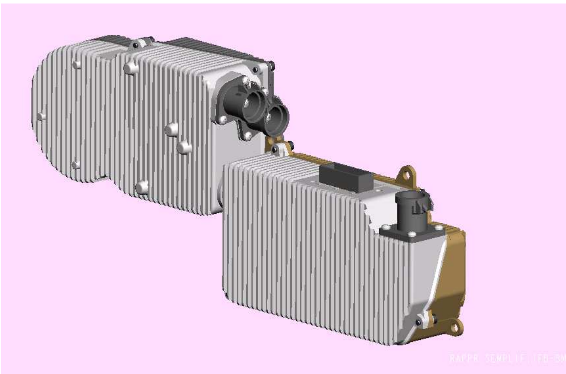

Figure 12: The BMI

The BMI supervises the battery operation, monitoring the main battery parameters like:

1) Current.
2) Terminal voltage.
3) Temperature.
4) State of Charge.
5) Insulation resistance between main circuit and battery box.

It provides all the connections between the battery and the vehicle.
It manages the battery taking in consideration the measured battery variables as the battery voltage, current and temperature. The controller estimates the battery SOC and keeps the battery working always within safe operating conditions. If an error occurs the BMI can disconnect the battery from the vehicle opening the main contactors.
It maintains the battery temperature within the right operative range using the external fan or the internal heaters.
The BMI consists of two main sections: the BMI unit and the IFB unit.
The BMI unit includes a microprocessor controlled board that performs the measurement of the parameters of the battery and the control of the battery operation. It has two sections, the High voltage and the Low voltage section and includes the connectors for the vehicle interface, the AC mains power and the battery charger. The IFB unit includes the connectors for the high voltage DC traction power, the main relays and the shunt for the on board current measurement.

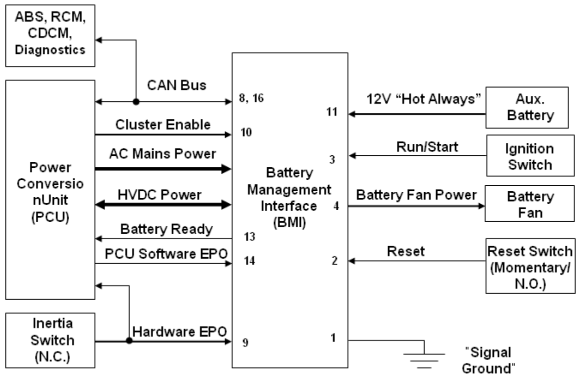

Figure 13: The BMI connection

As for the picture above, the power supply for the BMI-LV electronics may be derived from three different sources:

- From auxiliary battery DC supply on pin 11, when the ignition signal on pin 3 is present.
- From an external DC supply on pin 10 powered by the PCU when ACvoltage is connected.
- In case of low voltage absence of both battery DC supply and external DC supply, the BMI can be powered by a voltage converted from the ZEBRA® battery voltage. This internal DCDC source is not available in case of a cold or empty battery.

A step down DC/DC converter generates the power voltage for BMI-LV and BMI-HV circuits, but on a system level power supply from the 12V auxiliary battery is also required for operation of the main switches in the IFB (charging or discharging). The Hardware EPO signal indicates the status of the inertia switch. The inertia switch is a normally closed switch which opens when the vehicle is subjected to a significant mechanical shock (e.g. because the vehicle has been involved in a crash). An active Hardware EPO signal indicates that the inertia switch has been triggered. Since the Hardware EPO signal provides power to all high voltage contactors in the BMI, loss of the Hardware EPO signal will automatically cause all high voltage main contactor open.

The Reset signal indicates the status of the reset switch. The reset switch is a normally open, momentary switch mounted in the vehicle which can be used to force the BMI into the Off state. When the BMI is in the Off state, the battery pack will begin to cool down and will not use any of its internal energy to stay warm.

When the BMI receives a reset message via the CAN bus or detects that the reset input is active for more than 5 seconds continuously, the BMI initiates an orderly shutdown sequence and transition to the off state. As part of the BMI shutdown sequence, the BMI disables charging and discharging via CAN bus messages to the PCU. After charging and discharging are disabled, the BMI waits at least 1 second and then open the main contactors.

The BMI monitors the CAN bus for periodic messages from the PCU when any of the following conditions are true:

- *Condition 1:* Key Run is True.
- *Condition 2:* Charge Wakeup is True.

If Key Run or Charge Wakeup is True and the BMI receives CAN bus message at least once each second, the BMI sets PCU CAN Communication OK = True and can close the contactors in discharge or in charge mode.

If Key Run or Charge Wakeup is True and the BMI does not receive a valid CAN message at least once each second, the BMI sets PCU CAN Communication OK = False and it can not close the contactors for any reasons.

In all BMI operating states, the BMI determines whether mains AC power is connected to the vehicle (Acvoltage range of 85 – 265 VAC). The BMI periodically transmits mains AC power connection status to the PCU via the CAN bus.

The BMI is responsible for thermal management of the battery pack in all BMI operating states. The BMI controls the battery fan, AC heater and DC heater to maintain the temperature of the battery pack within appropriate limits under different operating conditions.

In the Off state, the battery fan, AC heater and DC heater are disabled.

When the battery pack temperature is above the maximum temperature limit associated with the current BMI operating conditions, the BMI enables the battery fan to cool the battery pack provided that at least one of the following conditions are true:

- *Condition 1:* The BMI is in Discharge state.
- *Condition 2:* Mains AC power is connected to the vehicle.

The battery fan is disabled when the battery pack temperature drops to or falls below the maximum temperature limit associated with the current BMI operating conditions. A little hysteresis is included in the battery fan control to prevent repeated on/off cycling of the battery fan near the battery pack thermal set points. In all BMI operating states, the BMI periodically transmits the battery fan status to the PCU via the CAN bus.

The ZEBRA®battery has two different heaters: the AC-heater and the DC-heater. The AC-heater, is powered by AC voltage and the DC-heater is powered by the ZEBRA®battery only.

The DC-heater is only operational if AC voltage is not available (except for the 80% SOC failed
Cell calculation).

When the battery pack temperature is below the set point associated with the current BMI operating conditions, the BMI enables the AC or DC heater as appropriate to heat the battery pack provided that the BMI is not in the Off state. The AC and DC heater are mutually exclusive and can not be enabled at the same time.

The battery heaters are disabled when the battery pack temperature reaches or exceeds the set point associated with the current BMI operating conditions. A little hysteresis is included in the battery heater control to prevent repeated on/off cycling of the battery heater near the battery pack temperature set points.

The BMI periodically transmits the battery pack voltage and current to the PCU via the CAN bus.

Current direction are defined as follows: positive current indicates current going out of the battery (discharge current) and negative current indicates current going into the battery (charging current). The BMI calculates the battery pack SOC during all BMI operating modes. The battery pack SOC is preserved when the BMI is in the Off state. The SOC calculation is compensated for battery pack self-discharge. The BMI periodically transmits the battery pack SOC to the PCU via the CAN bus.

The ZEBRA®battery is the main energy storage system on which the TH!NK *City* vehicle is based on. ZEBRA® is a registered trade mark for the technology of Sodium/nickel chloride warm batteries ZEBRA®batteries safety features make ZEBRA®batteries especially suitable for automotive applications like cars, vans and buses.

It can be used for any mobile or stationary energy storage application which requires more than about 2kWh of stored energy. ZEBRA®Battery technology has shown in laboratory tests that it provides a calendar life of more than 10 years and a cycle life of 1000-2000 nameplate cycles.

Figure 14: ZEBRA battery

This data is supported by batteries in the field, which are still in operation after more that 1000 nameplate cycles. They are fully recyclable as the battery material is used for stainless steel production: the nickel and iron content become part of the product and the salt and ceramic form the slag in a process consistent way.
ZEBRA®battery is a high temperature battery; the normal operating temperature for the cells is in the range 270-350°C.
The battery enclosure has a good thermal insulation thanks to the vacuum between the inner and the external box, and in normal condition a ZEBRA®battery will dissipate from its case some thermal energy (about 110W), depending on the battery type.
In particular on TH!NK *City* vehicle the ZEBRA®battery is the “Z36-371-ml3x-76” with a voltage of 371V, a nominal capacity of 76Ah and a complete energy of about 28.2KWh.
A typical charge time is 8 hours, and its maximum continuous discharge rate is C2.
A ZEBRA®battery is composed of single cells connected in series and parallel.
As for the picture below he open circuit voltage (OCV) of each single cell is 2,58V/cell and it is nearly constant over the complete operating range.

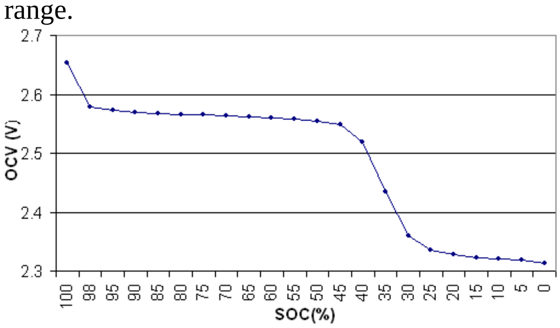

Figure 15: ML3X cell OCV

A ZEBRA®battery can operate in presence of failed cells with a reduced open circuit voltage because a cell typically fails to short circuit.

Each single cell in the charged state contains sodium as the negative electrode and nickel chloride as the positive electrode.
The sodium reacts with the nickel chloride on discharging to form sodium chloride (common salt) and nickel. The process takes place in the reverse direction on charging as described below.

$$2NaCl + Ni \underset{discharge}{\overset{charge}{\rightleftharpoons}} NiCl_2 + 2Na$$

All of these features make ZEBRA® battery the best solution especially for automotive applications like TH!NK *City* vehicle.

4.2.3 The motor

Figure 16: TH!NK *City* motor

The motor is a standard three phases Ac induction with a nominal power of 17KW a maximum power of 30KW and a maximum torque of 90Nm.

5 The operation of the new BMI software

Considering that some of the main parts of the TH!NK *City* are made from different suppliers it has been necessary to completely modify the standard BMI software to be able to correctly manage the entire system.
The main BMI operating states are defined as follows:

- Off.
- Power-Up.
- Park.
- Discharge.
- Charge.

The BMI software transits between operating states according to the state transition diagram shown in figure below.

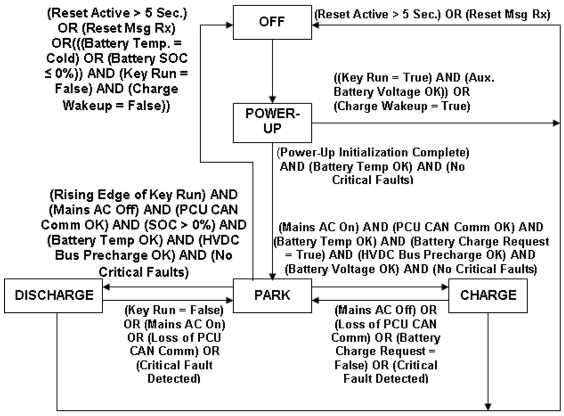

Figure 17: New BMI state transition

5.1 Off State

The Off state is a non-operational BMI software state. In the Off state, the BMI power supply is disabled and the BMI software is not working.

5.2 Power-Up State

In the Power-Up state, the BMI software performs a power-up self-test and BMI power-up initialization.
In the Power-Up state, the BMI performs cold-start initialization including a power-up self-test and low-level hardware and software initialization. At the conclusion of cold-start initialization, the BMI reports its status and configuration to the PCU via the CAN bus.
Upon entering the Power-Up state, the BMI performs a self-test to determine if it is capable of reliably performing its intended functions. Any fault detected by the BMI during that is considered a critical fault.
Following cold-start initialization, the BMI enables transmission and reception of CAN bus messages (in broadcast mode by default).

5.3 Park State

In Park state the vehicle is parked and the main contactors are open. In the Park state charging and discharging of the battery pack are not allowed.
In this status, normally the ignition is off, mains AC power is not connected to the vehicle, the battery pack temperature is above its minimum operating temperature and the battery state of charge (SOC) is greater than 0%.

5.4 Discharge State

In Discharge state the ignition is on, mains AC power is not connected to the vehicle, the battery pack temperature is within discharge limits and the main contactors are closed. In this state discharging of the battery pack (e.g. for vehicle propulsion) is allowed. Charging of the battery pack via regenerative braking is also allowed under certain conditions.

5.5 Charge State

In Charge state mains AC power is connected to the vehicle, the battery pack temperature is within charging limits and the main contactors are closed. In Charge state charging of the battery pack is allowed. Discharging of the battery pack is not allowed in the Charge state. In all BMI operating states, the BMI periodically transmits the BMI state to the PCU via the CAN bus.

5.5.1 New Charger algorithm

The charger for the TH!NK *City* is not a standard one from MES DEA, but built into the PCU. This meant it was necessary to study and design a new charger algorithm based especially on the PCU charger specifications.
When the pilot signal is present (the presence of a Pilot Signal indicates that there is a PCS-Portable Charging Station connected to utility power and the vehicle), the PCU continuously decodes the maximum available AC current based on the duty cycle of the Pilot Signal sent by the PCS.

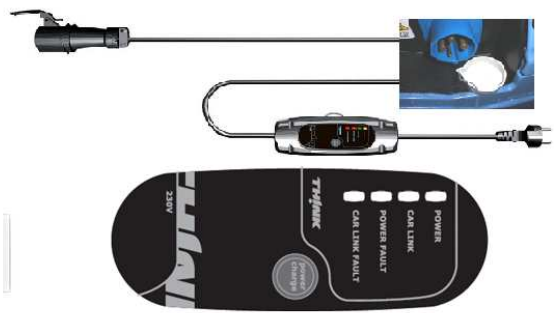

Figure 18: Portable Charging Station

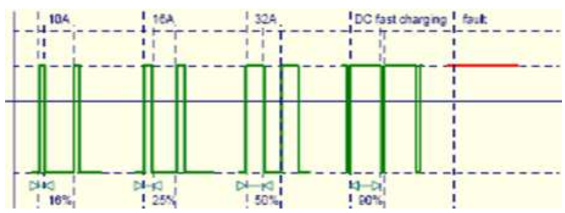

Figure 19: PWM Pilot Signal

If the Pilot Signal is not present, the maximum available mains AC current is set to zero. The PCU periodically transmits the maximum available mains AC current to the BMI via the CAN bus.

The BMI, then based on the available AC current controls the charge current through a PWM charger command sent to the PCU.
The BMI calculates and further limits the Charger PWM command to avoid exceeding the maximum battery limits or the main maximum current available on the ACnet considering the combined mains AC current loads of the charger and the battery Ac-heater used to maintain the battery temperature within the operative range.
The BMI respects the limits and the mains max current available calculating the power going into the battery during charge considering PCU charger efficiency. If the estimated Ac-current exceeds the maximum allowed for the BMI the maximum PWM is reduced.
The PWM dynamic and ramping have been optimized after special tests.
The charger is self protected against over current and voltage.
After the reaching of the end of charge, if the vehicle remains connected to the ACvoltage for more than one hour the BMI automatically restarts the battery charge and reaches a second end of charge. In the following picture is reported a graph of a typical battery charge.

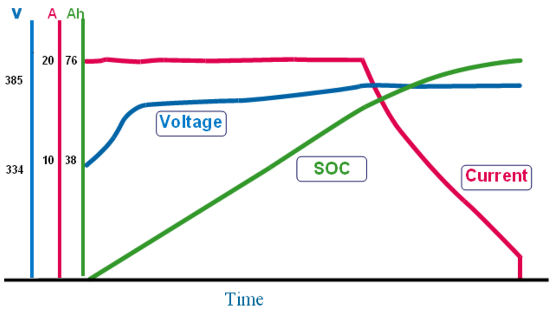

Figure 20: Graph of normal battery charge

In all the working conditions the BMI calculates the current, voltage and temperature limits and periodically transmits them via the CAN bus to the PCU. If a limit is exceeded the BMI sets an error and appropriate remedial actions are taken by the BMI and/or the PCU. The driver is notified the appropriate warning light on the dashboard. Subsequently if the PCU detects a malfunction or exceeded limit a message is sent to the BMI that can take appropriate action. With this management there is a double check on the system done by PCU and BMI.
During these months MES-DEA releases different BMI software versions. For each BMI software version MES-DEA and THINK engineers did all the validation tests on bench and vehicles to achieve the highest reliability level in all the different working conditions always keeping safety aspects and customer satisfaction in consideration. At the moment there are about 150 vehicles running on the streets without problems which proves the system reliability.

6 New BMI fault handling

A completely new fault handling has been designed (adding new errors and modifying the previous standard faults) considering all the possibilities for each different working condition.
A critical fault is defined as a fault where either discharging or charging the battery pack would create a potentially hazardous situation or cause damage to the vehicle. If the BMI detects a critical fault, the main contactors are opened immediately or after some delay depending on the actual fault. Each BMI error delay (before opening the main contactors) and its particular method of remedy has been analysed in detailed especially for this application.
In all BMI operating states, the BMI monitors itself for internal faults that can have a significant effect on critical BMI functions. When the BMI detects a critical internal fault, the BMI sets a corresponding internal fault flag on messages via CAN bus and immediately opens the main contactors. Depending on the actual fault characteristics healing of a fault condition is done at an appropriate time to ensure safe operation of the system under all conditions. Some faults conditions can be reset at the rising edge of Key Run is detected or ACvoltage is connected.
The BMI periodically monitors the electrical insulation between battery pack high voltage and vehicle chassis. In all BMI operating states, the BMI periodically transmits the current high voltage isolation fault status to the PCU via the CAN bus.

6.1 Main discharging faults

The BMI could reset some of the discharging faults conditions at the rising edge of Key Run or when Charge wake up is detected.

6.1.1 Discharge Undervoltage

In Discharge state, the BMI monitors the actual battery voltage vs. minimum discharge voltage. When the battery voltage falls below the minimum discharge voltage, for a certain time, the BMI sets the “Peak/Long deviation voltage min error”.

6.1.2 Discharge Overcurrent

In Discharge state, the BMI monitors the actual battery current vs. maximum discharge current. When the current out of the battery exceeds the maximum discharge current for a certain time, the BMI sets the “Peak/Long deviation current max error”.

6.1.3 Regen Overvoltage

In Discharge state, the BMI monitors the actual battery voltage vs. maximum regen voltage. When the battery voltage exceeds the maximum regen voltage for a certain time, the BMI sets the “Peak/Long deviation voltage max error”.

6.1.4 Regen Over current

In Discharge state, the BMI monitors the actual battery current vs. maximum regen current. When the battery current exceeds the maximum regen current for a certain time, the BMI sets the “Peak/Long deviation current max error”.

6.2 Main charging faults

The BMI periodically transmits charging fault status to the PCU via the CAN bus while mains AC power is connected to the vehicle.
The BMI could reset some of the charging faults conditions at the rising edge of Key Run or when Charge wake up is detected.

6.2.1 No Charge Current

In Charge state, the BMI monitors the commanded vs. actual charge current into the battery pack. When the Charger PWM Command is non-zero and no current is measured going into the battery pack for a certain time, the BMI sets the No Charge Current Fault. The BMI repeats different retries.

6.2.2 Charge Overvoltage

In Charge state, the BMI monitors the actual battery voltage vs. maximum charge voltage. When the battery voltage exceeds the maximum charge voltage for a certain time, the BMI sets the “Peak/Long deviation voltage max error”. When the BMI detects a Charge Overvoltage Fault, the BMI instantaneously opens the main contactors. If the battery open circuit voltage is higher than the limit the BMI does not connect the ZEBRA®battery to the PCU charger.

6.2.3 Charge Overcurrent

In Charge state, the BMI monitors the actual battery current vs. maximum charge current. When the current into the battery exceeds the maximum charge current for a certain time, the BMI sets the “Peak/Long deviation current max”.

6.3 Particular battery faults added

6.3.1 Battery Temperature Fault

In all BMI operating states, the BMI verifies the measured battery temperatures against a valid temperature range. If the BMI does not have access to any valid battery temperature measurements, the BMI sets the Battery Temperature Fault. When the BMI detects a Battery Temperature Fault, the BMI wait a certain time and then open the main contactors.

6.3.2 BMI Temperature Fault

It has been designed a special BMI temperature algorithm with new values after tests on vehicle. In all BMI operating states, the BMI verifies the measured BMI temperature against the valid temperature range and appropriate remedial action is taken.

6.3.3 CAN bus Timeout error

In all BMI operating states, the BMI verifies the received CAN bus messages sent by the PCU.
If for any reason the BMI does not receive these messages or the PCU fault has been detected , the BMI sets the error “Timeout message” and contactors will be opened or prevented form being closed.

7 New BMI and vehicle diagnostic tools

All MES-DEA diagnostic programs have been modified to support all the new CAN bus messages and errors. A vehicle diagnostic tool has been developed to ensure serviceability of all the vehicle systems. This to allow quick and easy fault tracing and repairs.
Since a lot of software modifications have been done for this special vehicle, MES-DEA engineers worked a lot to customize the standard diagnostic program called ZEBRAMonitor in order to support all the new functionalities, errors and algorithms.
With this MES-DEA diagnostic program that could be installed on a common personal computer, using a standard CAN bus interface (different types are supported), the customer could

check the main parameters of the battery (like number of cycles, days of operation,..), read the messages present on the CAN bus, download the BMI software or reset faults. There is also the possibility to perform different data acquisitions and save some battery life data as well.
HRM/Ritline Engineers based in Gothenburg has built an electrical rig where the complete

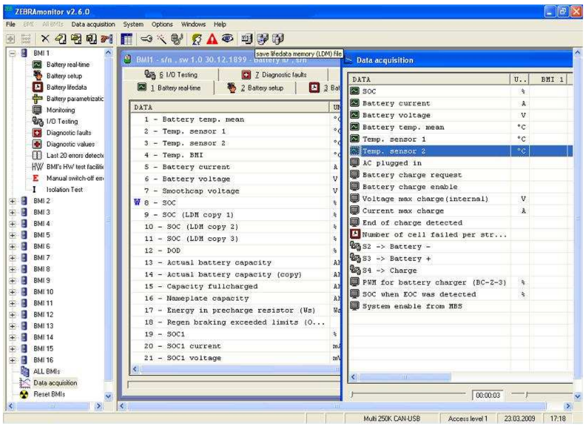

Figure 21: ZEBRA®Monitor diagnostic program

electrical system the TH!NK *City* has been built-up.
This rig has been a vital tool to get the diagnostic system to the status it has today.
Thorough verification has been conducted on the diagnostic system to give the mechanics the best possible resources and accuracy in getting the car fixed in short time during service and repair.
Special applications based on the main application used in workshops have been developed together with the application supplier. These applications are used to program important parameters during the later stages in production and also to verify the complete car after it has been built.

Figure 22: Vehicle diagnostic program

The application run on a PC and a VCI (Vehicle Communication Interface) is used to connect to the vehicle.

8 Future improvements

THINK and MES-DEA are continuously working on this project performing tests with different software versions and hardware improvements. Since the vehicles will be sold all over the world. THINK organizes service assistance centers in different countries with technicians trained to check with dedicated diagnostic tools the entire system.
The introduction of a new generation of ZEBRA®batteries with the Powerful Granulate X formula with ML3 cell capacity of 38Ah has already reduced the charging time and it will improve the stability of discharge performances along years with deep discharge.
TH!NK *City* will feature a Mind Box, a small computer containing both GPS and GPRS functionalities which enables wireless connectivity to the vehicle's system. With this solution, it will be possible to verify system and battery data.
The system can transmit state of charge and other vehicle statistics directly to the customer's mobile phone or personal computer. The Mind Box will give the driver direct connection to a customer service function, and will automatically call for assistance if a fault occurs. Fleet managers are able to both locate and control the charge rate for all fleet vehicles.

9 Conclusions

TH!NK *City* car has demonstrated in these years to be a real solution for electric vehicles meeting all the automotive standard requirements. ZEBRA® battery is the best solution to operate in the conditions described.
MES-DEA will continue to work on its ZEBRA® technology upgrading and improving it. Already 500 ZEBRA®batteries have been already delivered to THINK during last year. TH!NK *City* is currently produced in Norway and international sales has started. Following initial launch in Norway, THINK prioritized early deliveries in 2009 to Sweden, Denmark, Finland, Austria, Switzerland and the Netherlands. THINK is presently evaluating phase 2 European launch in Spain, France, Germany and the UK.

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