Date: 28th March 2024

Black Country Innovative Manufacturing Organisation (BCIMO)
RFQ Document

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1 Background

Black Country Innovative Manufacturing Organisation (BCIMO) have acquired an Ansaldo T69 tram from its previous service life. The tram will have been electrically checked for safety and any required rectifications made prior to the start of the project.
The primary purpose of the vehicle is for use as a test mule for rail innovations, such as autonomous driving, fuel cell powertrains, battery powertrains etc. BCIMO wish to run this vehicle on their 2.2km track. However, the track does not have a catenary (overhead wire) system to supply electricity.

The purpose of the project is to provide an electrical energy source (battery) and associated charging / management / safety and control equipment to enable the tram to be operated at a given max duty cycle without the use of an overhead power system.

BCIMO are considering adding a battery to replace of the overhead wire supply, does not integrate with the vehicle electronics and to respect the battery limits, relies on driver-in-the-loop feedback via a visual display of current draw and on robust battery disconnection via e.g. Mosfet switches.

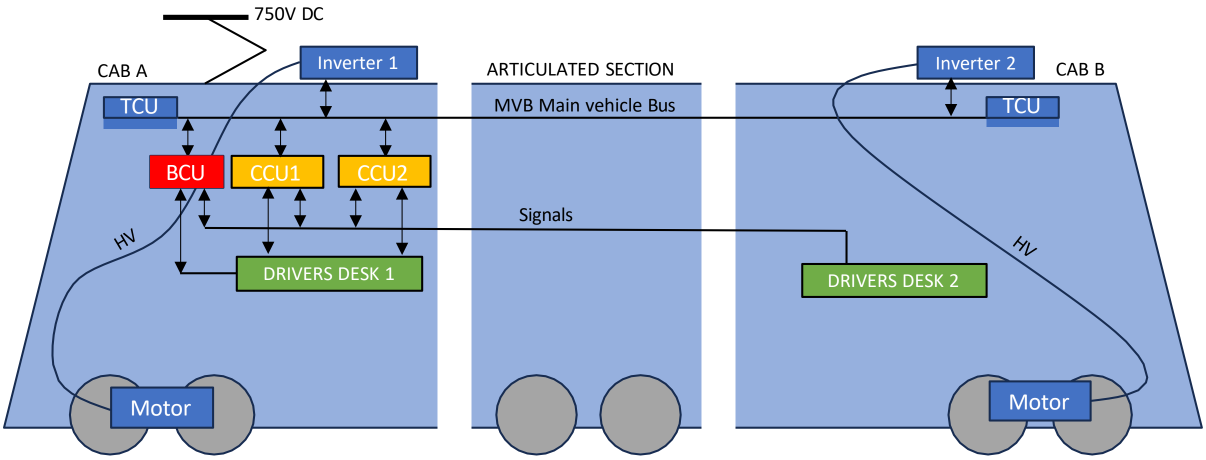
This document describes the requirements in order for applicants to submit an RFQ.

2 Current layout

The layout of the tram is described below. Note that a considerable amount of documentation for the tram is available and dates suggest that the design took place circa 1999. Useful excerpts from the documentation are available in ‘Appendix 2 – Useful Excerpts from archive documents’.

Figure 1 – T69 Birmingham Tram No16

The electrical layout of the vehicle is as per the diagram below;



High voltage architecture – The HV Architecture is described below;

- 750 Vdc arrives at the pantograph (usually via a catenary system). The current from this supply is passed via a circuit breaker to the inverters and then to the motors driving the front and rear bogies. The inverters use IGBT's and these are controlled by the Traction Control Units (TCU's), which create the driving wave-form for the inverters.

Control architecture – The main control systems on the vehicle consists of;

- Drivers desk – There is a drivers desk at each end of the vehicle, designated CAB A and CAB B, which each contain a 'cab enable' key switch, a forward/reverse/park brake/ lever and a 'tractive effort' lever which provides the signal for driving and braking. Note that the tractive effort lever attempts to provide consistent vehicle performance despite changes in weight, and its signal is modified depending on weight signals provided by the suspension system. The signal is sent to the CCU's via an RS485 data bus.
- CCU1 – This is the Central Control Unit (CCU), which takes the drivers signals and distributes outputs to the Traction Control Units (TCU's) (One per inverter) and Brake Control Unit (BCU).
- CCU2 – The second CCU is a monitoring unit, which independently receives the signals from the driver's desk and monitors the actions of CCU1 to act as a failsafe.
- TCU – As noted above, the two traction control units each create the waveform to drive their individual inverter based on the tractive effort and direction instructions.
- BCU – The Brake Control Unit (BCU) can choose to deploy regen braking, hydraulic foundation braking, track brakes (magnetic) and a 'sanding system' which deploys sand onto the track to increase the coefficient of friction between wheel and rail during emergency braking. Note that the regenerative braking system includes a 'chopper' within the inverter and a braking resistor sized to be able to deliver full braking torque of the vehicle continuously until stopped.

Further details of these systems are available in Appendix 2 – Useful Excerpts from archive documents and Appendix 3 – Relevant documents in the archive.

3 Risk mitigation

The calculations and assumptions given in this document are based on the best information available at the time of writing. It is the responsibility of the supplier to check and make their own calculations to ensure the suitability of their systems and ensure the correct functionality of the vehicle.

4 Proposed Solution

The tram will need integration items to work with a new energy store and we are inviting you to prepare a quotation based on the following information.

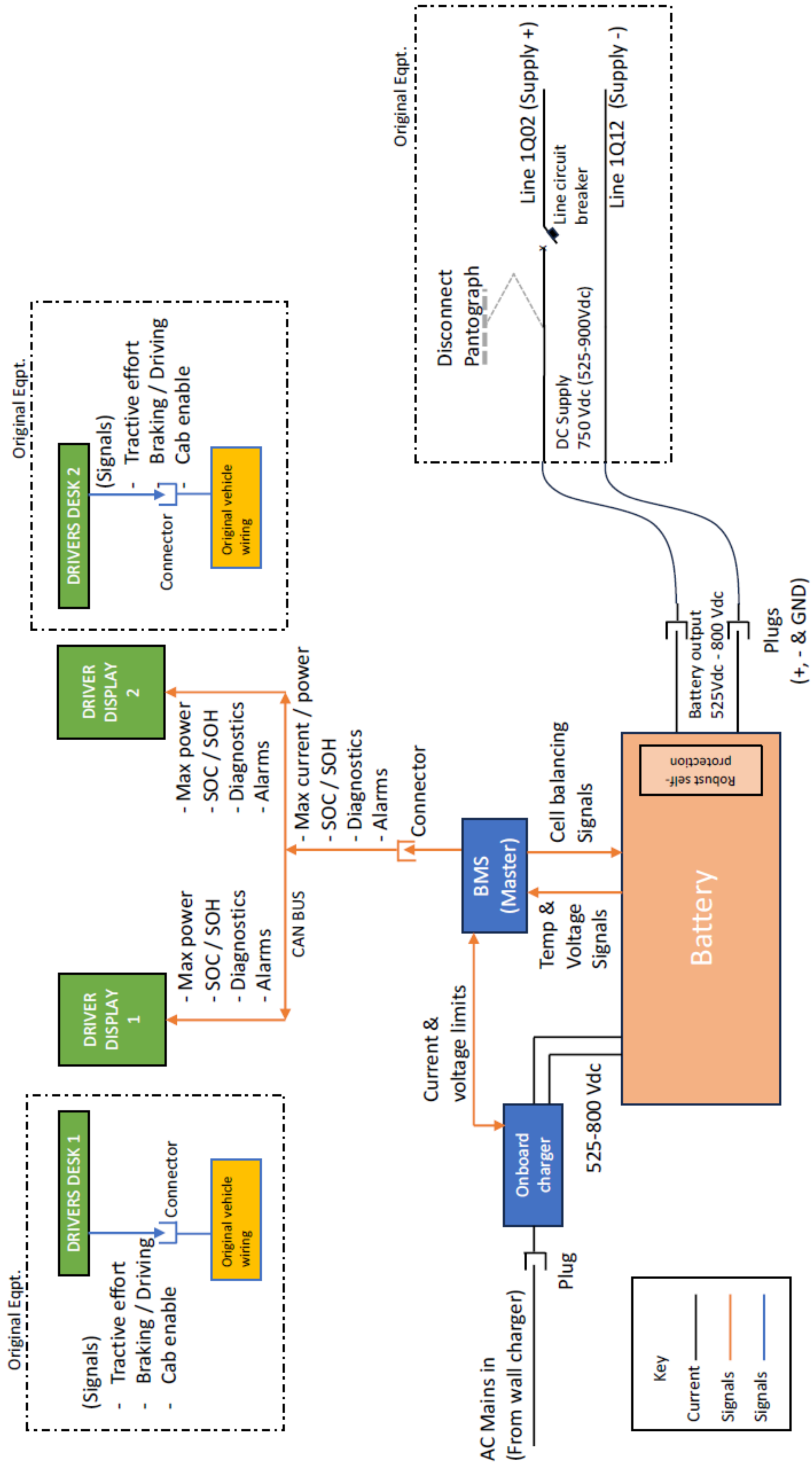
As a reminder, BCIMO have purchased a tram which usually operates a 750Vdc overhead wire electrical supply. BCIMO's track does not have an overhead wire capability. This project is intended to enable the tram to run by adding an energy store (battery) and ensuring safety of operation. This quick and dirty version of the project requires a battery and charger installation along with robust protection mechanisms.

The objective of this project is to get the tram up and running as quickly as possible. In this configuration, the new equipment is not required to communicate with the existing infrastructure. Information is provided via a display screen to enable driver feedback.

Outline of expected works;

- An on-board battery will be fitted to the vehicle in order to provide motive power as a replacement for the overhead wire. This will necessitate disconnection of the pantograph and reconnection of the battery in its place.
- The battery specification is outlined in 'Appendix 1 – Battery calculation'. It is anticipated that the battery will be 500Vmin - 800Vmax, around 150-200kWh **useable energy** and capable of charging at 115kW during regen braking. The larger end of this size range will be required if regen is not active.
- For lowest cost, an off-the-shelf battery product is preferred.
- The battery can be located inside the vehicle as the seats have been removed and access via the tram doors is provided.
- A new driver display will be fitted into both the front and rear cabs to relay information from the battery, such as; a graph of 'current draw' with minimum and maximums marked upon it, a bar graph of temperature (Showing max and min operating limits), as well as battery statuses (SOC, SOH, etc). This driver information enables to driver to drive the vehicle within the operating limits of the battery
- A robust disconnect mechanism, capable of disconnecting hundreds of times without damage (e.g. a Mosfet switch) will be fitted to the output of the battery, with an internal control system that opens the disconnect in the event that battery temperature, voltage or current limits are exceeded.
- The supplier will fit an on-board charger, capable of converting the 22kW-90kW AC supply from an external wall-charger to a DC supply to the battery to facilitate overnight charging of the battery.
- It is anticipated that the BMS master will be based on automotive hardware and will communicate with the charger, as well as the driver displays. For this reason it is anticipated that the communications will be via CAN Bus, though other communication protocols are permissible.
- The new equipment will be tested by trial-runs in the tram on-site.
- No communications between the new electrical hardware and the existing tram RS485 data bus are required but would be considered an advantage in order to protect the battery.

Figure 2 – Vehicle outline



- Description of scope

  BCIMO anticipate that your quotation will include the following scope;

  - Solution description
  - Price and timing breakdown
  - Review of documentation, I/O & communications protocols
  - Site visit to measure wiring loom lengths & assess connector types
  - Proposal of electrical hardware
  - Proposal of software
  - Transport & installation of electrical hardware
  - Validation & calibration of software
  - Operator training
  - H&S Training
  - After sales support (Day rates)
  - Proposal to deal with end of life disposal / recycling

We have undertaken initial calculations for battery size which are detailed in the Appendix 1 – Battery calculation and these are based on the following assumptions;

Table 1 – Simulation input data

Item	Value
Spec sheet values:	
Vehicle weight:	39,500kg +10%
Motor continuous power:	210kW x 2
Parasitic load (HVAC etc)	13kW
Assumptions:	
Frontal area:	2.434m x 3.625m = 8.823m^2
Coefficient of Drag:	0.532
Traction coefficient:	0.35
Rolling resistance coefficient:	0.002
Max vehicle speed:	40km/h
Average acceleration / deceleration:	0.5m/s^2

Duty cycle

The table below specifies a MAXIMUM duty cycle and assumptions to arrive at the duty are explained in 'Appendix 1 – Battery calculation'.

Table 2 – Duty cycle data

Item	Value
Life:	7 Years
Days/yr of use:	100 days / yr
Hours of use per day:	3 hours / day
Duty:	
- Step 1	Accelerate from 0 to 40 km/h over 22.2 seconds (Average 0.5m/s^2)
- Step 2	Constant speed 40km/h for 27.7 seconds,
- Step 3	decelerate from 40km/h to stationary over 22.2s (Average 0.5m/s^2)
- Step 4	Repeat steps 1-3 for 3 hours per day. Charge overnight at 22kW-90kW.

Battery specification

We anticipate that the successful supplier will make use of an off-the shelf battery from a commercial vehicle application, with additional control systems work to match the communications protocol specified by the integration project above.

The physical space for the battery in the tram is large as all seats have been removed. Access is through the tram doors, which may preclude some battery form factors.

The calculations and assumptions made in order to determine this battery specification can be found in 'Appendix 1 – Battery calculation'.

Table 3 – Desired Battery specification

Item	Value
Absolute energy	250 kWh
Useable energy	200 kWh
Voltage range	525 – 900 Vdc
Peak discharge power (30s)	200 kW
Peak charge power (30s)	115 kW
Overnight charge power	22 kW-90kW
Weight	Free
Chemistry	Free
IP Rating	IP67
Homologation	Passed UN ECE Reg 100
On-board charger	22 kW -90kW AC → DC Bus

5 Appendix 1 – Battery calculation

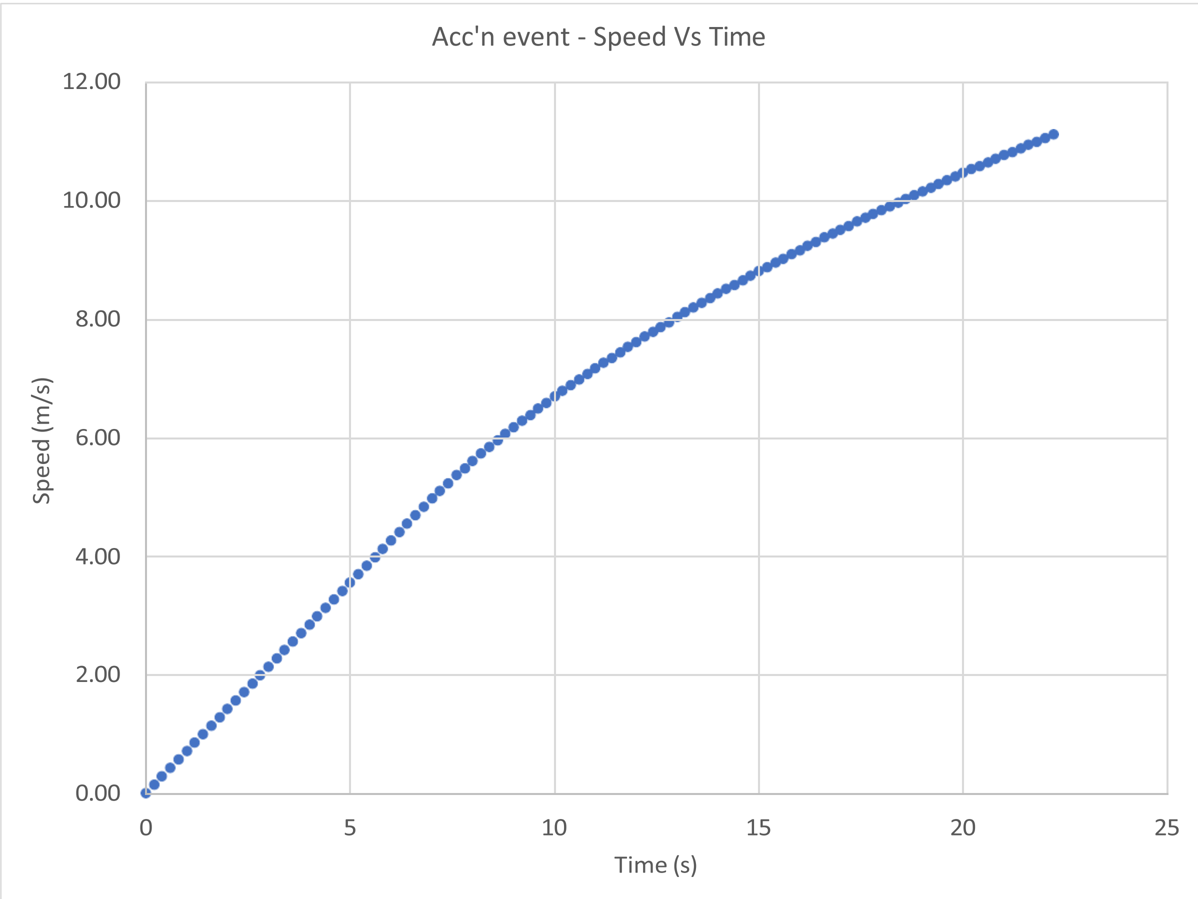
5.1 Battery size

We have undertaken some battery size calculations by firstly simulating the performance of the train. The basic vehicle parameters are given in the drivers handbook.

Mass (Including passengers): 43,450 kg
Width: 2.434 m
Height: 3.625 m
We have assumed a Cd of 0.532 based on the following study;
[Source: https://iopscience.iop.org/article/10.1088/1757-899X/184/1/012015/pdf]
Traction coefficient: 0.35
[Source: https://en.wikipedia.org/wiki/Adhesion_railway#:~:text=For%20steel%20on%20steel%2C%20the,to%20as%20low%20as%200.05.]

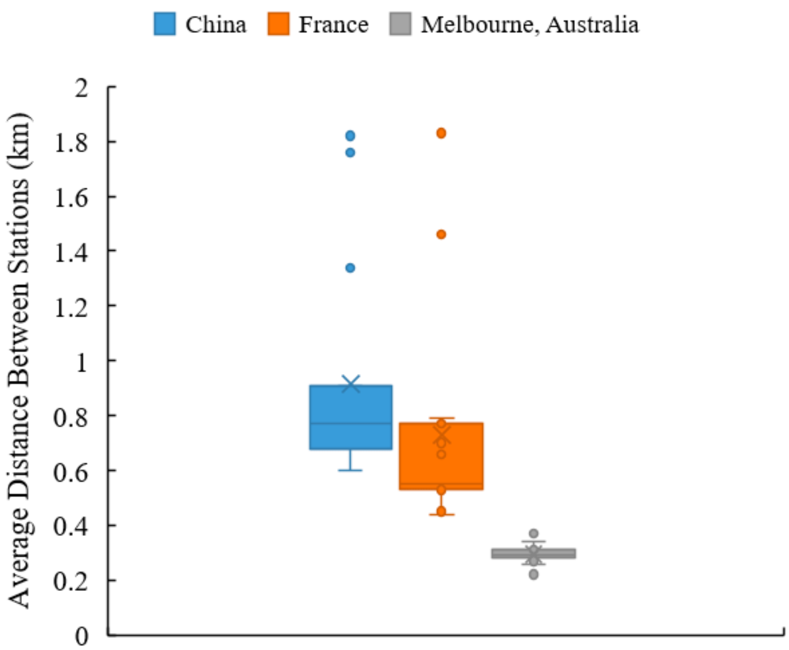
This gives the performance as shown in the graph, where acceleration to 40km/h takes 22.2 seconds.

Figure 3 – Speed Vs distance



The tram covers just shy of 150m during this 22 second period. We have studied typical duty cycles for trams and find a distance of approximately 600m to be a reasonable assumption (see following diagram).

Figure 4 – Distance between tram stops



Source: [https://www.researchgate.net/figure/Distributions-of-average-distances-between-stations-of-tram-lines-in-different-countries_fig3_346376804]

The duty is thus;
Accelerate 22s, 146m distance – (150kW motor power + 13kW LV systems).
Const speed 27.7s, 308m distance – (17.5kW motor power + 13kW LV systems).
Decelerate 22s, 146m distance – (-150kW* motor power + 13 kW LV systems).
Idle at stop 30s (Embark / Disembark time), 0 distance – (13 kW LV systems only).
*Note negative number indicates regen braking

If we assume this duty cycle for the 600m distance between stops, we see that the energy balance, including conversion efficiency of 90% for battery and 86% for electronics, is;

Table 4 – Energy balance between stops

	Time (s)	Traction energy (kWh)	Ancillary energy (kWh)	Total energy (kWh)	Distance (m)
Accel event	22.2	1.029	0.104	1.132	146
Const Speed	27.7	0.135	0.129	0.264	308
Decel Event	22.2	-0.582	0.104	-0.479	146
Idle	30	0	0.140	0.140	0
Totals				1.057 kWh	600m

For a **three hour shift**, this means 1.057 kWh per 0.03 Hours, the total energy consumption is; 1.057 kWh x (3/0.03) = **111.8kWh** and **average power** of 1.057kWh / 0.03h = **37.3kW.**

We also note that a 112 kWh battery, being charged at a rate of 115kW (150kW less efficiency losses) during regen, means a C-rate of 1 in charge. Modern cells are capable of high peak charge rates, and a typical continuous charge rate of 1 C is common.

What if we don't regen?
Looking back to Table 5, we see that the energy consumed between stops was 1.057 kWh, however, 0.582 kWh was recharged into the battery during regenerative braking. If we eliminate regenerative braking as an option, to reduce installation complexity, the energy consumption between stops becomes 1.057 + 0.582 = 1.639 kWh between stops.
For a **three hour shift**, this means 1.639kWh per 0.03 hours, the total energy consumption is; 1.639 kWh x (3/0.03) = **173 kWh** and **average power** of 1.639 / 0.03h = **57.8kW.**

Battery size recommendations;
We would recommend an absolute battery size of **150-250kWh**. This would limit regen capability to 150-250kW arriving at the battery (1-C charge rate), the remainder would have to go to the braking resistor.

Assuming 200kWh useable energy and 37.3kW average power consumption (regen is active), the battery would last 200kWh / 37.3kW = 5 hours and 22 mins of full duty operation between charges.

The larger end of battery capacity will ensure a longer life (see calculation below) and the option to either run longer days or have larger parasitic loads.

5.2 Battery life calculation

BCIMO would like the vehicle to have a 7 year useable life. And realistically it might be used for an average of 100 days a year (The rest being down-time for instrumentation and changing control system specifications), and an average use of 3 hours during these days. Thus the total number of hours of use would be; 7 x 100 x 3 = 2,100 Hours.
Given that a typical lithium ion cell has an expected life of 1,500 – 2,000 cycle, this means that the battery should be able to be used for 2,100 Hours / 1,500 cycles = 1.4 hours (84minutes) between charges or more if we are not to exceed the cell cycle life.

As previously calculated, the energy will be used at a rate of 37.3kW, meaning 37.3 x 1.4 = 52kWh of useable energy is required in the battery if we are not to exceed its life. Note that to ensure a long life, the battery should be charged up to 90% SOC and discharged down to 10% SOC, meaning the minimum capacity of the battery should be 52 / 0.8 = 65 kWh (Absolute). This is in line with the above recommendations.

6 Appendix 2 – Useful Excerpts from archive documents

6.1 Overall HV layout;

1.7 PROPULSION ELECTRICAL EQUIPMENT

1.7.1 PROPULSION EQUIPMENT OVERVIEW

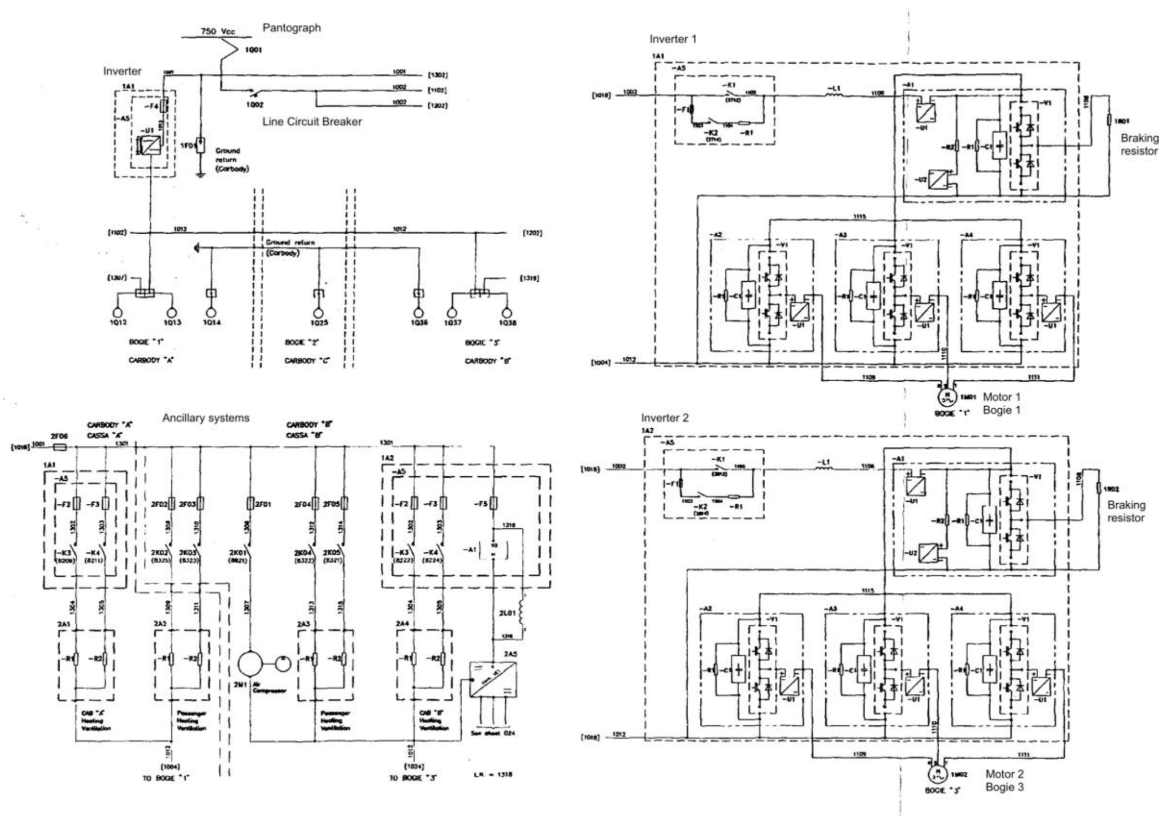
The propulsion electrical equipment mainly consists of two VVVF (variable voltage, variable frequency) inverters,one inverter for each motor bogie, each one feeding the asynchronous traction motor. See HV functional scheme Figure 1.17.
The drive results to consist of the following equipment:

A. 1 pantograph	(1Q1)
B. 1 lightning arrestor	(1F5)
C. 1 protection main circuit braker	(1Q2)
D. 2 main line contactors	(1K1÷1K2)
E. 2 pre-charge circuits of the filter capacitors	(1F1-1R1-1K5÷1F2-1R2-1K6)
F. monocell L - C line filters	(1L1-C1 ÷ 1L2-C1)
G. inverters complete with control	(1A1÷1A2)
H. braking choppers complete with control	(1A1-V2 ÷ 1A2-V2)
I. braking resistors	(1R5 ÷ 1R8)
J. traction motors	(1M1÷1M2)

The drive system allows the following configurations to be implemented in a static way:

- running direction	(forward, reverse)
- running mode	(traction, coasting and braking)
- electrodynamic braking	(regenerative or dissipative).

Therefore the electro-mechanical equipment is minimized.
The drive of each motor-bogie is functionally independent, and thus vehicle operation is possible even in case of failure of a drive.



6.2 Low voltage systems

The DC/DC converter is used to supply auxiliary power from catenary voltage 750 Vdc (525-900Vdc). The DC output provides 28 Vdc for low voltage supply and battery charging in current voltage (I/U) model.

- Technical data

A. Input:

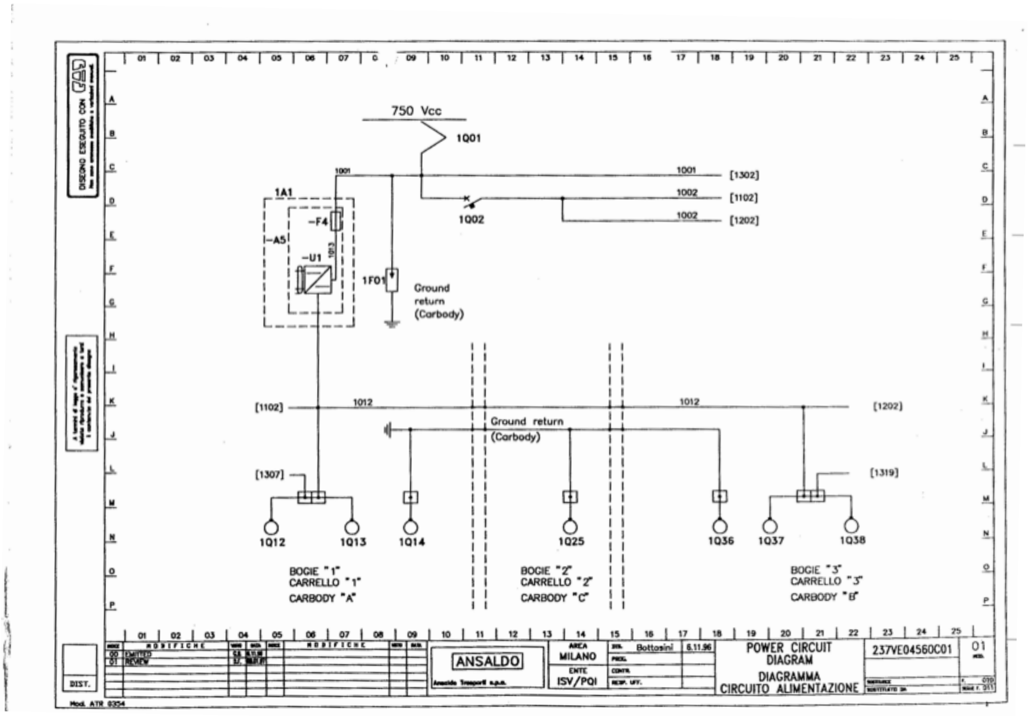
Nominal Input Voltage	U_N= 750	Vdc
Input Voltage Range	U_I= 500 to 900	Vdc

B. Output:

(LVPS and Battery Charging):

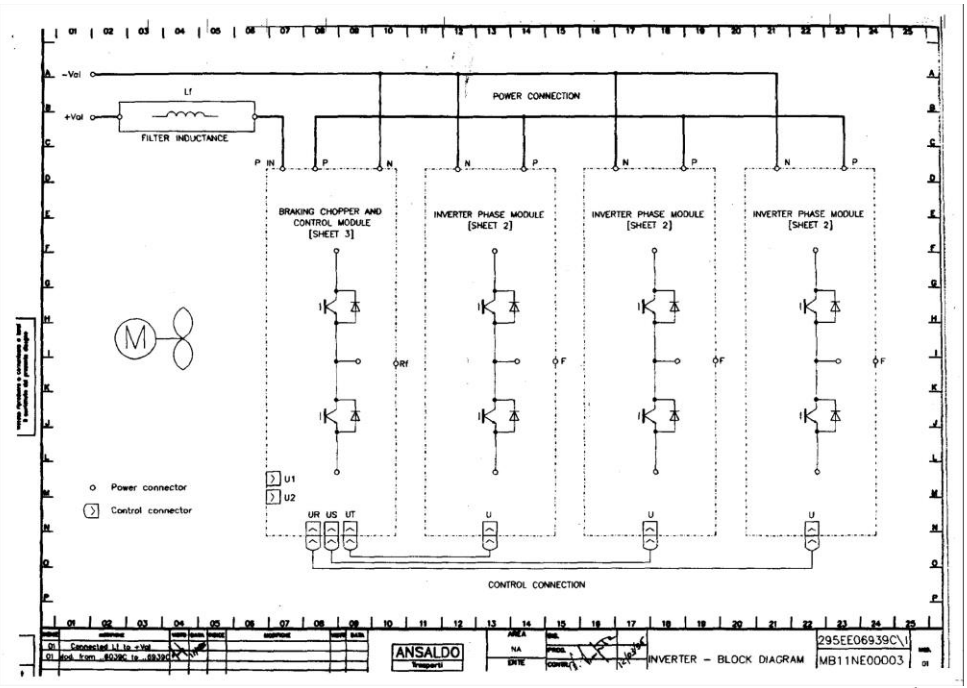
Nominal Battery Voltage	U_B=24	Vdc
Battery Charging Voltage	U_{BC}.30	Vdc
Battery Maintenance Voltage	26.8	Vdc
Max Output Current	I_T=450	A
Output Power (total)	13.5	kW

6.3 Pantograph



6.4 Inverter specification;

Consisting of three identical interchangeable power modules which mount the IGBT's, the snubber circuits, the protection and drive electronics, the filter capacitors, the current and voltage transductors.



INVERTER CHARACTERISTICS	
Rated input voltage	750 Vdc
Input voltage range	525-900 Vdc
Maximum first harmonic frequency	152 Hz
Maximum traction power at 562 Vac	480 kVA
Maximum braking power at 635 Vac	900 kVA
Efficiency	0,97

BRAKING CHOPPER CHARACTERISTICS	
Operating voltage	900 Vdc
Maximum peak power	700 kW

The filter capacitors are mounted inside the inverter modules, with discharge resistors permanently connected across their terminals.

To reach the required capacity, six capacitors are connected in parallel, each one featuring:

CAPACITOR DATA	
Capacity	1 mF
Mean continuous voltage	750 Vdc
Peak repetitive voltage	1000 Vdc
Rms current	100 A

6.5 Motor specification;

Traction motor data:

- Motor type	3-phase, squirrel cage induction motor	
- Ventilation	self-ventilated	
- Number of poles		4
- Frequency range	1 to 130	Hz
- Voltage range	5 to 562	V a.c.
- Insulation class		IT 200
- Protection degree		IP 25
- Continuous rating :		
. voltage (phase to phase)	462	V
. power	210	kW
. frequency	54.3	Hz
. stator current	345	A
. speed	1630	rpm
- Dimensions (WxLxH)	505x814x505	mm
- Weight	750	kg

6.6 Braking system

The vehicle has a combination of 'Electro-dynamic' braking (Inverter/chopper) and friction braking (Hydraulic pistons & accumulators) in addition a sanding system operates to provide additional traction (by spraying sand at the contact patch between wheel and rail) either by driver request or automatically in the case of emergency braking.

Control system function - The CCU receives the braking effort request from the driver's desk and distributes it to the Braking Control Units (BCU's) and TCU's. Pressure transducers on each bogie transmit vehicle load information to the BCU's and this is passed on via the CCU to the TCU to control the inverter / chopper.

The electro-dynamic braking system firstly attempts to regen to the overhead line and if it finds that the line does not accept this it swaps to regen through the braking resistors, so that maximum electrical braking is available at all times.

Both dynamic brake and friction brake have their own anti-slide (ABS) capability.

The anti-slide function of the friction brake is performed collecting the speed information from all the 2 motor bogies and 4 independent wheels of the vehicle, generating a so called "ideal wheel speed". In the event of slide, the braking effort is conveniently reduced (on a bogie basis, then the effort is re-applied, with a jerk-ramp limitation.
In the event the trailer-bogie motor pump is failed, if the system acts three times in a short time-interval, due to strongly degraded adherence conditions, the anti-slide is cut-off (on the trailer bogie) to avoid to empty the accumulator.

The anti-skid function of the dynamic brake acts on a bogie basis. Each TCU receives the speed information (independent from the brake system), from its own bogie, and performs the anti-skid function calculating the expected deceleration rate, related to the selected braking mode. If deceleration rate exceeds that expected, braking effort is suitably reduced, until wheel speed has come back to the correct value.

In the event of a skid, sanding devices are automatically called, to achieve enhancement of adherence coefficient. (Sand is sprayed at the contact patches).

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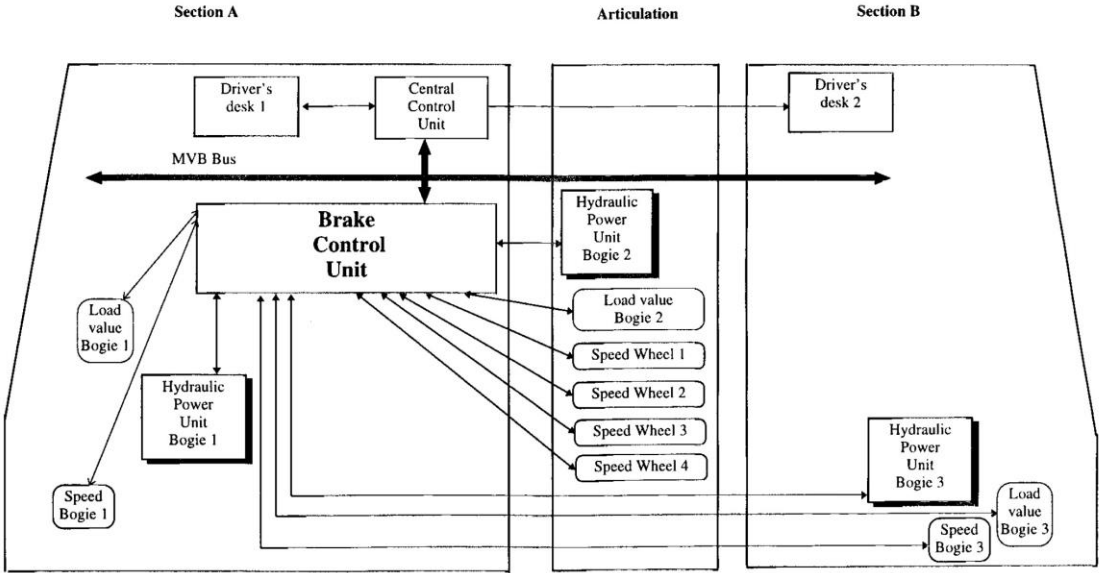
Title: **LRV-Birmingham / Electro-hydraulic Brake Description**

Figure 2: Brake system configuration



6.7 TCU
Spec: 16 Bit microprocessor
Inputs – Motor current, line voltage, motor speed, inverter temperature
Outputs – Driving signals (galvanically insulated) to IGBT's

Functions – System interface, analog signal processing and protection logic, inverter regulation, chopper regulation, control logic of power switching

The TCU acquires signals from the CCU via the RS485 serial link. These include machine state (traction, braking, coasting), train direction (forward, reverse), state of electromechanical equipment and torque reference.

6.8 Antenna system ATP

For restricted sections of track, passive track-side beacons signal threshold limits to the tram. If the driver does not obey these limits (e.g. speed) the tram automatically begins to brake the vehicle to a STOP, assuming the driver is unresponsive. This system can be overridden by using a switch to the left of the driver controls, however, this limits the maximum vehicle speed to 15 km/h.

6.9 Control system standards / references

The vehicle has a central control unit (CCU), with a redundant secondary CCU unit.

The vehicle also has two traction control units, one for each traction inverter. They are located close coupled to their respective traction inverters. The function of the TCU's is to create the sine-wave form and drive the IGBT gates directly.

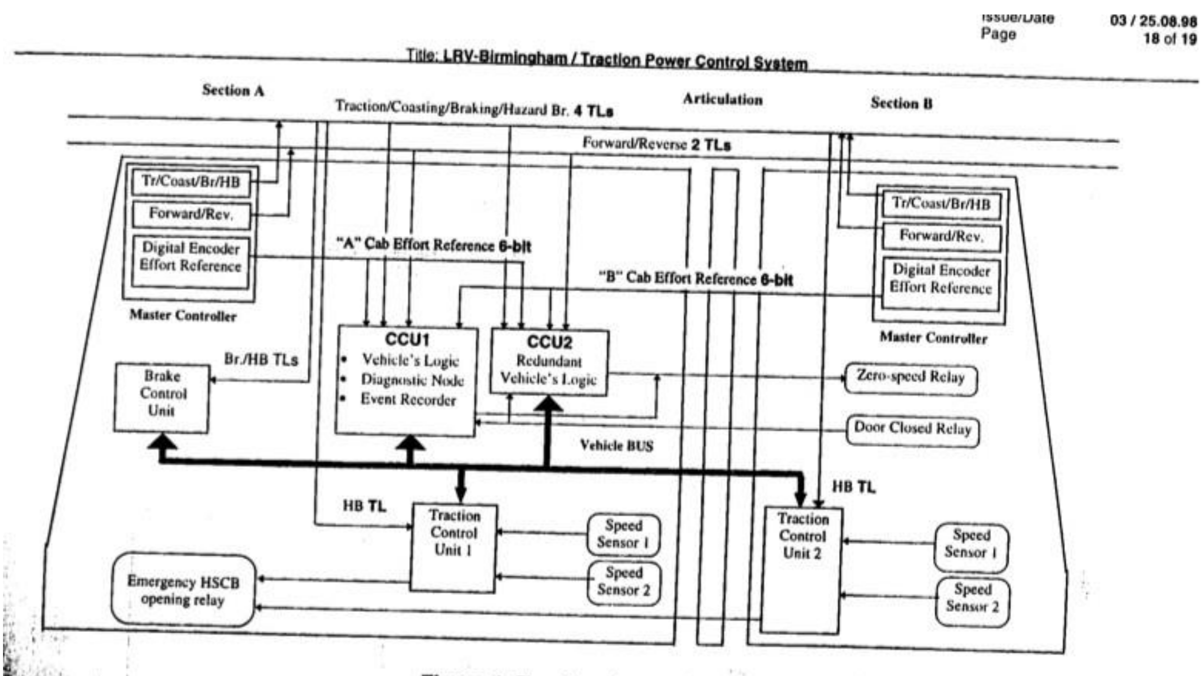


Figure 1: Traction Power Control System

Ansaldo Trasporti s.p.a.

A great deal more information relating to the control system can be found within the archive.

7 Appendix 3 – Relevant documents in the archive

- Drivers handbook - MB1.1NP.00002-01.PDF

- Description of control system - 293VE05464B-03.PDF
- Traction inverter / braking chopper specification - 234EE06939B.1--.PDF
- CCU hardware architecture & signal I/O - 234EE07220B-05.PDF
- Data logger event list - 253EE24008B-03.PDF

- Electro-hydraulic braking system description - 293VE04605B-01.PDF
- Braking hydraulic schematic & electronic I/O - 371VE02685B--.PDF
- Sanding system - 02022005--.PDF

- High Voltage Scheme - 236VE04561F01-02.PDF

- List of drawings - MB1.1NY.00020-05.PDF

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