HIGH-CLASS TRANSIT IN AALBORG

POWER SUPPLY

PRELIMINARY POWER SUPPLY DESCRIPTION FOR LRT SYSTEM
TECHNICAL NOTE
APRIL 2014
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1  Resumé

Dette arbejdsnotat indeholder foreløbige resultater fra analysen vedrørende strømforsyning af en første etape for Aalborg Letbane.

Med udgangspunkt i en række opstillede forudsætninger (32 m letbanetogsæt, 12,2 km samlet linje, 750 V jævnstrømsforsyning, 20 km/t rejsehastighed, maksimal 3 minutters frekvens mv.) er antallet af nødvendige omformerstationer blevet opgjort til i alt 8 stk. Den indbyrdes afstand mellem omformerstationerne på linjen kan være mellem 1,3 km og 2,0 km afhængigt af strækningens gradient, driften og tootypen.

Fysikoverslaget for strømforsyningen (omformerstationerne uden risikotillæg, køreledninger mv.) udgør i alt 62 mio. kr.

I den videre bearbejdning af projektet skal beregningerne af systemets belastning optimeres gennem detaljering af inputdata og simulering med henblik på at fastlægges placeringen af omformerstationerne mere præcist.

2  Executive summary

This technical note gives the preliminary results regarding the power supply infrastructure for the first line of tramway in Aalborg.

Based on preliminary assumptions (of which a tramway length around 32m, a 12,2km line length, 750 V DC voltage, a 20km commercial speed, a 3mn headway, etc.), the number of traction substation is preliminarily estimated to about 8 substations. The distance between two traction substations could be between 1.3 to 2 km depending on the profile, train operation and type of train retained.

The corresponding cost for power supply infrastructure is estimated to 8,330,000 € (excluding risks provisions, OCS, multitubular costs, etc.).

In the next phase, traction calculation shall be realized and optimized by computerized simulation with fixed input data to consolidate the preliminary estimation and to fix with more certainty the location of the traction substations along the line.
3 Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LRT</td>
<td>Light Railway Transit</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage</td>
</tr>
<tr>
<td>OCS</td>
<td>Overhead Catenary System</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
</tbody>
</table>
4 Codes and standards

The main power supply standards to be used are listed below. All the equipment’s shall be in accordance with the appropriate Danish national standards, Euro Norms and any other applicable standards to ensure that the power supply equipment supplied and its installation fully meet the reliability, maintainability and availability criteria to be defined in further stage.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 60 076 (parts 1 to 12)</td>
<td>Power Transformers</td>
</tr>
<tr>
<td>IEC 60 146</td>
<td>Semi-conductor converters</td>
</tr>
<tr>
<td>IEC 60 364 (parts 1 to 6)</td>
<td>Low-Voltage Electrical Installations</td>
</tr>
<tr>
<td>IEC 60 850 and EN 50 163</td>
<td>Railway applications – Supply voltages of traction systems</td>
</tr>
<tr>
<td>IEC 60 913</td>
<td>Electric Traction Overhead Lines</td>
</tr>
<tr>
<td>IEC 60 947 (parts 1 to 7)</td>
<td>Low-Voltage Switchgear And Controlgear</td>
</tr>
<tr>
<td>IEC 61 850</td>
<td>Communication networks and systems for power utility automation</td>
</tr>
<tr>
<td>IEC 62 040 (parts 1 to 3)</td>
<td>Uninterruptible Power Systems (UPS)</td>
</tr>
<tr>
<td>IEC 62 271 (parts 1, 3, 100 to 107, 200 to 202)</td>
<td>High-Voltage Switchgear And Controlgear</td>
</tr>
<tr>
<td>IEC 62 305-4</td>
<td>Protection against lightning - part 4: electrical and electronic systems within structures</td>
</tr>
<tr>
<td>H07 RNF</td>
<td>Specification for isolated copper cables with non-rigid armature</td>
</tr>
<tr>
<td>NF C 13-100 or equivalent</td>
<td>High Voltage Electrical Installation.</td>
</tr>
<tr>
<td>NF C 13-200 or equivalent</td>
<td>High Voltage Electrical Installation - Additional Rules.</td>
</tr>
<tr>
<td>EN 50 119</td>
<td>Railway Applications - Fixed Installations - Electric Traction Overhead Contact Lines</td>
</tr>
<tr>
<td>EN 50 121 (parts 1 to 5)</td>
<td>Railway Applications - Electromagnetic Compatibility</td>
</tr>
<tr>
<td>EN 50 124 (parts 1 &amp; 2)</td>
<td>Railway Applications - Insulation Coordination</td>
</tr>
<tr>
<td>EN 50 126-1</td>
<td>Railway Applications - The Specification And Demonstration Of Reliability, Availability, Maintainability And Safety (Rams) - Part 1: Basic Requirements And Generic Process</td>
</tr>
<tr>
<td>EN 50 153</td>
<td>Railway Applications - Rolling Stock - Protective Provisions Relating To Electrical Hazards</td>
</tr>
<tr>
<td>EN 50 160</td>
<td>Voltage Characteristics Of Electricity Supplied By Public Electricity Networks</td>
</tr>
<tr>
<td>EN 60 439</td>
<td>Low-Voltage Switchgear And Controlgear Assemblies</td>
</tr>
<tr>
<td>EN 61000</td>
<td>Electromagnetic Compatibility</td>
</tr>
<tr>
<td>U 1000 RO2V</td>
<td>Specification for isolated copper cables with rigid armature</td>
</tr>
<tr>
<td>U 1000 ARO2V</td>
<td>Specification for isolated aluminium cables with non-rigid armature</td>
</tr>
<tr>
<td>UTE C 15-103</td>
<td>Low-voltage installations and corresponding equipment - selection of electrical equipment (including wiring systems) in relation to external influences</td>
</tr>
<tr>
<td>UTE C 15-105</td>
<td>Low voltage electrical installations - simplified method of calculating cross-sectional area of conductors and selection of protective devices</td>
</tr>
<tr>
<td>UTE C 15-106</td>
<td>Low and high voltage electrical installations - cross-sections of protective conductors, earthing conductors and equipotential bonding conductors</td>
</tr>
<tr>
<td>UTE C 15-107</td>
<td>Low-voltage installations corresponding equipment - methods for fixing characteristics of busbar trunking systems and selection of protective devices. Simplified method and general method</td>
</tr>
<tr>
<td>UTE C 15-443</td>
<td>Protection of low-voltage electrical installations against over voltages of atmospheric discharges and switching - selection and erection of surge protective devices</td>
</tr>
<tr>
<td>UTE C 18-510 &amp; 18-540</td>
<td>Collection of general provisions for electrical safety</td>
</tr>
</tbody>
</table>
5 Introduction

The aim of this document is to give an overview of the feeding mode for traction power system for Aalborg LRT (light railway transit) project.

6 Operational environment

The main characteristics of the line are:

- Line length: 12.2 km
- Number of passenger’s stations: 24
- Depot: 1 (end of line)

The line will have a power supply network to provide 750 VDC to the rolling stock.

This voltage will be produced through power traction substations, which converts alternative current to direct current.

The current distribution is ensured by the catenary system and the return current is ensured by the rails, through the wheels bandage of the LRT.

Passenger’s stations and some equipment (on line) are supplied with low voltage (230/400 VCA) from traction substation or local provider.

<table>
<thead>
<tr>
<th>Station number</th>
<th>Name</th>
<th>Station number</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Norden</td>
<td>13</td>
<td>Humlebakken</td>
</tr>
<tr>
<td>2</td>
<td>Marina</td>
<td>14</td>
<td>Danalien</td>
</tr>
<tr>
<td>3</td>
<td>Vesterkærer</td>
<td>15</td>
<td>Gronlands torv</td>
</tr>
<tr>
<td>4</td>
<td>Haraldslund</td>
<td>16</td>
<td>Scoresbysundvej</td>
</tr>
<tr>
<td>5</td>
<td>Vestbyen St</td>
<td>17</td>
<td>Pendlerpladsen</td>
</tr>
<tr>
<td>6</td>
<td>Borgergade</td>
<td>18</td>
<td>Gigantium</td>
</tr>
<tr>
<td>7</td>
<td>Østerå</td>
<td>19</td>
<td>Pontoppidanstræde</td>
</tr>
<tr>
<td>8</td>
<td>Administrationsbygningen</td>
<td>20</td>
<td>Universitetet</td>
</tr>
<tr>
<td>9</td>
<td>J.F. Kennedys Plads</td>
<td>21</td>
<td>Bibliotekskolen</td>
</tr>
<tr>
<td>10</td>
<td>Politigården</td>
<td>22</td>
<td>Selma Lagerlöfs Vej</td>
</tr>
<tr>
<td>11</td>
<td>Karolinelund</td>
<td>23</td>
<td>Servicebyen</td>
</tr>
<tr>
<td>12</td>
<td>Bornholmsgade S</td>
<td>24</td>
<td>Universitetetshospitalet</td>
</tr>
</tbody>
</table>
Figure 1: Aalborg LRT Network
7 Installations

7.1 Platform and tracks
Along the platform runs a multitubular network (composed by sheaths) where power and communication cables are installed. Depending on the configuration of the platform, the multitubular network can be central, side or double side.

The dimensions of the platform enable punctual traction power or power cables crossings (traction and LV).

The structural characteristics of rail (including its resistivity) and the connection of two ways by negative equipotential bondings improve proper flow of current return.

7.2 Traction Substations
They concentrate HV equipment, Traction equipment (transformation and distribution), LV equipment (transformation, distribution, electrical command).

The Traction power network will be used by the rolling stock.

The LV power will provide electrical energy to the auxiliary equipment of the traction substation, passenger’s stations, operation room, signaling room, and some online equipment.

Traction substations can also accommodate other equipment such as signaling, transmission, video, etc.:
- In traction substations with partitioning and separate access;
- In adjacent room (to traction substations) such as signalling room or operation room.

7.3 Overhead Catenary System (OCS)
The catenary could be made of one 150 mm² copper wire by track. To improve current conduction, a connection with a large section cable is made regularly through paralleling cabinet.

The position of the cabinet is obtained by a simulation of traction sizing. These cabinets could be located on line or on stations.

Additional positive equipotential bonding between the 2 wires of catenary will be positioned regularly.

7.4 Passenger’s station
Passenger’s stations include equipment for their own power supply and occasionally some equipment for the traction network.
Power is supplied from traction substations or from the local provider thought cabinets when the distances are too long.

To be compliant with environmental and esthetical constraints, electrical equipment of different users are grouped into technical cabinets integrated at the passenger’s station.

7.5 Operation and control center
LRT network is designed to be managed remotely from the Operation and Control Center (OCC). Strategic equipment are then remotely command (circuit breakers, switches, ventilation, etc.) and monitored (temperature alarm, over voltage, blown fuse, etc.). The OCC is usually localized in the depot.

7.6 Traction architecture
Typically, we find 2 types of architecture for traction substations for LRT network:

- “π” traction substation with an up and down separation of the traction substation,
- “T” traction substation with a direct link to the catenary.

Traction substations generally feed the line in parallel, which means that an electrical section could be fed by more than one traction substation. Then DC circuit-breakers need to have a secure interlocking one with the other. Every DC circuit-breaker feeding the same electrical section shall be opened when one of them opens due to a short-circuit.

Both architectures are illustrated in the figures hereunder.
Figure 2: “π” traction substation architecture

Figure 3: “T” traction substation architecture
8  Description of the 750 V DC Feeding System

8.1  Traction philosophy
The main criteria for the traction substations implementation are to have no operation failure with one traction substation out of order on three consecutive (whatever traction substation on the lines). If two consecutive traction substations are in failure, the operation will automatically be downgraded.

In this logic, it is better to have, as far as possible, the HV feeding coming from different HV loops for 3 consecutive traction substations. Furthermore, for reliability reason the HV feeding shall be in cut-off mode rather than in antenna mode.

8.2  Traction substation
The feeding mode below is the most used for LRT networks.

Traction substations could be fed by the utilities through the 20 kV (or 10 kV if existing) grid, widely available across the whole urban area.

For Traction power, the voltage is then lowered and rectified into 750 V DC through a 12-pulse rectifier.

For the Low Voltage power, the voltage is lowered into 400 V AC, 50 Hz.

Traction substations are generally mainly composed of:

**High Voltage**
- HV (20 or 10 kV) incoming cells and HV protection cells. This equipment could located in a separate room (if required by the power utilities) and connected to the utilities network in cut-off mode (preferable feeding mode for redundancy and then reliability reasons). The availability of the 20 or 10 kV network has to be discuss locally.

**Transformer and rectifier group**
- One oil-type or dry transformers (the power will be defined later, (1,000 MVA as a first approach),
- One 12-pulse rectifiers (preferred to 6-pulse to lower harmonics currents brought back to power utilities.

**Traction distribution**
- High speed circuit breaker(s) and various switches and isolators to separate the Traction network if necessary.
8.3 Depot
The traction substation of the depot will supply power to the area of the depot and for the line. That’s why the traction substation of the depot has two transformer and rectifier groups. Consequently, the size of the traction substation in the depot is larger than the other traction substations. It could mainly be identify as a double traction substation.

The traction substation of the depot is similar to an online traction substation. It has more

HV (10 kV) incoming cells and HV protection cells,
- One transformer,
- One 12-pulse rectifiers,
- One circuit breaker,
- One traction switchgear for the depot.

8.4 Type of traction substation
Traction substations could be erected through 3 different types:
- Classical solution,
- Buried solution which implies a larger footprint and disadvantages in terms of maintenance,
- Prefabricated concrete or metallic shelter.

The choice has to be decided during the basic design phase, through the following constraints:
- Land availability,
- Architectural constraints,
- Works duration constraints.
8.5 Classical traction substation
Here is an example of classical traction substation but an existing building can also be used to install power supply equipment.

![Clermont-Ferrand classical traction substation](image)

Figure 4: Clermont-Ferrand classical traction substation

8.6 Shelter traction substations
Those traction substations are made of 2 half-shelters (about 2 x 24 m²) inside which all equipment are already installed in factory, except for the traction transformer due to its weight. The equipment arrangement is then optimized.

![Shelter traction substation in Mulhouse](image)

Figure 5: shelter traction substation in Mulhouse

A shelter traction substation can also be buried.
8.7 Footprint

The table below summarizes the need in the area based on the configuration of traction substation:

<table>
<thead>
<tr>
<th>Simple traction substation (line)</th>
<th>Overhead</th>
<th>Buried</th>
</tr>
</thead>
<tbody>
<tr>
<td>[75 m² – 90 m²]</td>
<td>[100 m² – 120 m²]</td>
<td></td>
</tr>
<tr>
<td>Double traction substation (depot)</td>
<td>[95 m² – 110 m²]</td>
<td>[110 m² – 130 m²]</td>
</tr>
</tbody>
</table>
8.8 Implantation examples

Here are two examples of traction substation implantations:

*Figure 6: Overhead traction substation*
Figure 7: Buried traction substation
9 Number of traction substations

The aim of this part is to quantify the number of traction substations needed to supply traction power to the rolling stock.

The estimated number of traction substations is made on the basis of similar projects having similar characteristics and on the following elements:

- Length and alignment of the line;
- Operation data;
- Type of rolling stock.

The number of traction substation is not yet based on the calculation software Marcadet.

The data taken into account are summarized below:

- ≈ 32m long rolling stock
- 12,200 m line length fully electrified with catenaries;
- 750 V DC voltage;
- 900 kW rectifier and 1000 kVA transformer;
- 150 mm² copper wire catenary;
- 1,000 mm² feeder cable;
- Load (with passengers) : 57 t;
- 3min of headway (in anticipation of shorter headways related to the implementation of LRT phase 2);
- 20 km commercial speed.

9.1 Results

The number of traction substation is about 8. The distance between two traction substations could be between 1.3 to 2 km depending on the profile, train operation and type of train retained.

Note: Between “Borgergade St” station and the "Ostera” station, convoys of exceptional great heights may cross the tram platform. The simpler solution to allow the crossing of these convoys, without height limit, is a free OCS zone.

In case that solution is retained, a readjustment of the positions of substations may be necessary and/or reinforcement of electrical connection of the OCS free zone with feeder cables. In the worst case, a substation may be necessary to rebalance the distances between substations. If retained as a solution, computerized simulation will help to check the impacts of the free OCS zone.

Reloading supercaps in the station require more powerful substation to provide energy to the moving trains and train in loading mode.
9.2 Traction calculation

In the next phase, traction calculation will be realized and optimized by computerized simulation (Marcadet software) with fixed input data to locate precisely the traction substation.

The simulation shall be run absolutely taking into account a consolidated headway in order to optimize the number and location of traction substations. In the same way, connexion and extension of LRT Aalborg project must be known.

The network grid in Aalborg shall be given as an input data in order to build traction substation, as far as possible, close to the HV (High Voltage) network in order to avoid overcosts due to high length of cable to be unwind for connection (combined to trenches to be dug into the city).

9.3 Required input data for traction calculation

The list of required data to ensure a traction calculation is indicated below:

**Line and operation**

- Alignment (including profile)
- Length
- Curves
- Station position
- Headway
- Dwell time
- Operation (nominal and downgraded modes)
- Operational speed (according the curves and the alignment)
- Priority crossroads
- Partial services

**Depot**

- Train in preparation
- Number of tracks in the workshop
- Train movements

**Rolling stock**

- Type
- Number of car
- Length
- Width
- Frontal surface
- No load mass
- Speed limit
- Acceleration
- Deceleration
- Regeneration
- Nominal voltage
- Auxiliary power
- Traction acceleration versus speed curve
- Traction electrical power versus speed curve
- Maximum recovery voltage
- Regenerative braking power versus speed curve

9.4 Main issues associated with a 750 V DC feeding system

The main advantages of the 750 VDC feeding mode for an LRT line are:

- Very commonly used all around the world;
- 20 or 10 kV feeding for traction substations easily feasible;
- OCS implementation highly feasible from an aesthetical point of view.

With a line electrified in DC mode, some known problems can occur. These are mainly with:

- Harmonics brought back into the Utilities network;
- Rail/ground touch voltage;
- Stray currents.

Note: From a standard and technical point of view, 1500 V DC electrification of a LRT network is feasible, but the cost to develop a compliant rolling stock could lead to shorter bidder list.

9.5 Harmonics

The connection of an electric installation of non-linear type (the rectifier of a traction substation) on a distribution network will generate harmonic currents. These harmonic currents are themselves also generating harmonic voltages and it is imperative that all new installations follow the utilities regulations. In order to avoid the installation of filters, the use of a 12-pulse rectifier is recommended rather than a 6-pulse rectifier$^1$.

$^1$ Another study on the specification of harmonics should be undertaken to recommend the filters necessary for each traction substation in basic design or detailed design phases depending on the type of bid to tender.
9.6 Rail/ground touch voltage
Due to trams running and due to electrical isolation of the tracks, a voltage appears between the rails and the ground. This voltage shall always be under 120 V (as a continuous value) and 60 V in workshops to be in conformity with EN 50 122-1 standard.

9.7 Stray currents
In DC railway electrical systems, rails are used to return the electrical current towards the traction substations. The voltage drop in the rails can generate potential differences between the rails and the ground and current leakage into the ground. These extraneous currents flowing through soil and/or water, known as “stray currents”, cause electrochemical corrosion damage to metal structures, or reinforcement in contact with, or below ground. Low resistance between the traction return rails and the ground allows a significant part of the return current to leak into the ground.

Preventative and/ or corrective action can be taken to protect assets against the dangers of corrosion created by stray currents. The main methods for cathodic protection differ according to the type of structure that is affected by these stray currents.

Corrective actions consist of installing drainage type or cathodic protective equipment. This type of protection is effective on metallic and continuous ducts which have a good electric conductivity.

*Note: Water, Telecom & Gas utilities have to be invited in order to explain them the effect of stray currents and how to be immunized.*

9.8 Braking energy saving
Nowadays tramways are equipped with braking energy saving. When braking, motors become generators and the braking current is sent back on the OCS. In normal mode, the recovery rate could be between 20 to 30%.

We could try to recover more braking energy by using:

- Inverter: extra braking energy is sent back to power utilities,
- Supercaps and batteries: installed in traction substations, they could stock a part of the extra braking energy to give it back when a tram is in traction. This method is already used in France on the LRT system in Le Havre,
- Supercaps on-board: this is the optimum solution because there is no loss when the current flows through the OCS. Nevertheless this solution shall be implemented on each rolling stock unit.
### 10 Unit costs

The hypotheses for the calculation of investment costs are as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Prices (€)</th>
<th>Quantity</th>
<th>Amount (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple 750 V DC traction substation and online equipment: including design, supply, delivery, installation, testing and commissioning of all equipment, but excluding civil works, Utilities connection and land acquisition.</td>
<td>700,000</td>
<td>7</td>
<td>4,900,000</td>
</tr>
<tr>
<td>Double 750 V DC traction substation and traction equipment in the depot: including design, supply, delivery, installation, testing and commissioning of all equipment, but excluding civil works, Utilities connection and land acquisition.</td>
<td>1,400,000</td>
<td>1</td>
<td>1,400,000</td>
</tr>
<tr>
<td>Spare parts (excluding delivery)</td>
<td>150,000</td>
<td>/</td>
<td>150,000</td>
</tr>
<tr>
<td>10 kV connection cost based on French experience assuming the 10 kV network is close to the traction substation.</td>
<td>30,000</td>
<td>8</td>
<td>240,000</td>
</tr>
<tr>
<td>Civil works for simple 750 V DC traction substation.</td>
<td>180,000</td>
<td>4</td>
<td>720,000</td>
</tr>
<tr>
<td>Civil works for double 750 V DC traction substation.</td>
<td>230,000</td>
<td>1</td>
<td>230,000</td>
</tr>
<tr>
<td>Civil works for simple 750 V DC traction substation on flood plain. (uplifted)²</td>
<td>230,000</td>
<td>3</td>
<td>690,000</td>
</tr>
</tbody>
</table>

These costs are based on French rates which were increased by a ratio about 1.3. This ratio corresponds to the costs difference generally noticed between France and Denmark on infrastructures.

² The substations located in the flood plain are considered in this estimate as uplifted (not buried). In case they were buried, they would be some extra costs to consider on civil works.
These costs exclude:

- Any Risk provisions
- Costs for multitubular network within platform (civil works costs)
- OCS costs
- Measurements (harmonics, stray current, emc)
- Inverter equipment on traction substations
- SCADA equipment for traction power
- Workers base camp