Grid Compatible Flash Charging Technology

TOSA e-bus infrastructure

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Abstract—Together with various partners, ABB has developed a flash charging system for electric buses with corresponding infrastructure, charging stations and on-board propulsion technology, which meets the requirements of grid codes, public transport services, city planners and passengers.

ABB's flash charging technology for electric buses is a zero-emission, low-noise alternative to diesel buses and does not require any expensive installation of overhead lines, which have a negative impact on the cityscape. With its roof-mounted charging contact the bus connects automatically and in less than one second with special flash charging stations at stops and charges its battery within 15 - 20 seconds while passengers get on and off. To avoid placing high peak short duration demand on the grid, the energy can be stored in a wayside battery next to a charging pole.

Thanks to an innovative electrical drive system, energy from the roof-mounted charging equipment can be stored in compact batteries, along with the vehicle's braking energy, powering both the bus and its auxiliary services, such as interior lighting or air conditioning. ABB worked together with Geneva's public transport company (Transports Publics Genevois, TPG), the Office for the Promotion of Industries and Technologies (OPI) and the Geneva power utility (Services Industriels de Genève, SIG) on this project.

A phased approach has been adopted to implement this technology. The TOSA project started with the demonstrator and based on its success, the flash charging method is now progressing to the first high-capacity electric bus line planned to be commercially operated within a larger fleet at line 23 in Geneva by 2018.

Keywords-component; flash charging station; power quality; city bus; charging infrastructure; AC/DC converter; TOSA

I. INTRODUCTION

The TOSA flash charging system is the first of its kind all-electric articulated bus developed as a viable alternative to diesel-powered buses. It can carry up to 143 passengers (the specific TOSA bus for TPG that will run in Geneva in 2018 can carry up to 132 passengers). It is inherently safe because the charging points are only energized when the bus is actually connected. Because it uses a direct electrical connection, concerns over electromagnetic fields can be mitigated. Furthermore, not requiring the installation of heavy equipment under the roadway simplifies the installation process and reduces the associated disruption.

I. E-BUS CHARGING INFRASTRUCTURE SYSTEMS

There are different charging methods for electrical buses, as shown in figure 1

A. Overnight charging

Overnight charging (or *Depot charging*) is a name widely used to identify the 'traditional technique', where the operator charges the bus usually at the depot for several hours with low power until it leaves with a full battery and repeat the process each night. Therefore, it is crucial that the on-board batteries have sufficient capacity.

B. Opportunity Charging

The second concept is known as Opportunity Charging (*OppCharge*, *Terminals only or DC Fast charging*); the buses are typically charged at the terminal stations or at strategic points along the route via DC fast-charging with charging powers between 150 to 600 kW for a several minutes. The bus can travel longer distances without coming back to the depot.

C. Flash Charging

The third concept is the one implemented in TOSA: the Flash-Charging method. It takes the Opportunity Charging concept a step forward, allowing smaller on-board batteries than other e-bus systems, which only charge at terminals, and smaller still than those that only recharge in depots. Therefore in the depot TOSA needs a significantly lower power connection to the grid than other systems, which means there is a far better chance that the existing depot's electrical supply will have enough spare capacity to accommodate a TOSA system. If the supply network needs to be upgraded, the costs to upgrade to a TOSA system will be lower compared to others. Additionally, as TOSA only needs a relatively short time for charging its batteries a single depot infrastructure unit can be shared between multiple buses.

Furthermore, TOSA is designed to function on lines with high capacity and high frequencies. It meets the onerous demands of main lines in cities during rush hours.

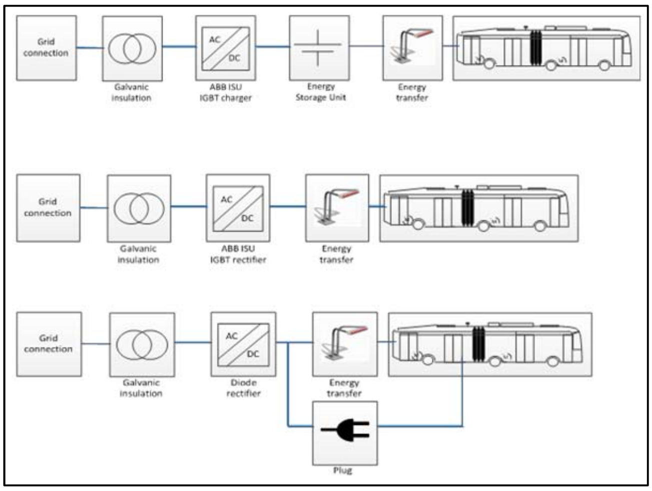

Figure 1. TOSA flash-, terminal- and depot feeding stations

II. Transport Passengers Not Batteries

One fundamental difference between buses and cars is that buses follow fixed routes. The question of “range of operation” which is of significance to electric cars is reduced to the more manageable “distance to next recharging opportunity” for a bus. With buses predictably stopping at regular intervals, charging points can be located at the stops. With the bus being able to top up its charge at these points, the need for large and heavy batteries is avoided and the vehicle becomes lighter, more agile, more energy efficient as well as providing more space for passengers inside. Furthermore, if charging time can be limited to the time that the bus needs to stop anyway, negative effects on the schedule can be avoided.

The high-power (600 kW, 20 seconds) charging of the high-power density batteries on the bus can result in load peaks affecting the local grid. The flash charger station, however, flattens out the demand by charging batteries located on the wayside over a period of a few minutes while drawing a lower current from the grid. As this current is up to 10 times less than it would be the case without storage, the connection can be made with a cheaper and more readily available low-power supply. With limited time being available at stops (passengers typically embark and disembark in 15 to 25 seconds), as little time as possible should be lost in establishing the electrical connection – the Energy Transfer System does this in under a second. A laser aligns the moving equipment on the bus roof with the static overhead receptacle and connects automatically with the charging pole. The connection is made as soon as the brakes are applied.

III. TOSA Infrastructure Configuration

The change from diesel to electric supply should not reduce the commercial average speed nor require an increase of the fleet size to provide the same service. It was this requirement that led to develop two types of feeding stations along the route plus one for the depot. The composition of flash stations, terminal chargers and depot chargers depends on individual characteristics of the bus line or the bus line network, as shown in Figure 1.

As described, the flash stations provide a short high power boost of energy. However, drawing 600 kW for 15 to 20 seconds is not sufficient to recharge the batteries fully. More prolonged charges of four to five minutes at 400 kW are delivered at the terminal stop where buses are scheduled to stop for longer periods. The time required for recharging at the terminal stop should not risk causing the bus to fall behind its schedule. Figure 2 shows an energy-simulation on a bus route and the effect of the charging stations on the state of charge.

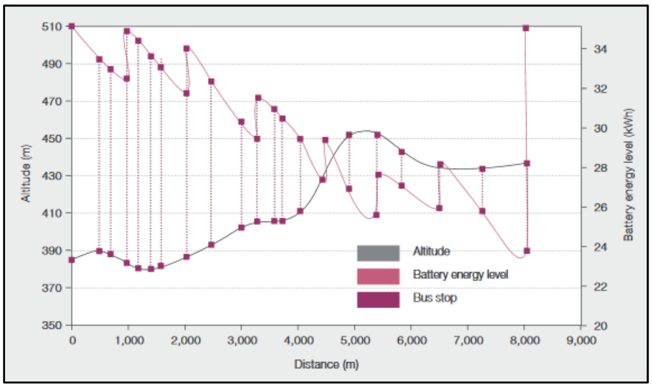

Figure 2. Example of a figure caption. (figure caption)

The following compose the charging infrastructure:

- TFS (Terminal Feeding Station), 3-5 minutes fast charging at each terminal stop;
- FFS (Flash Feeding Station), 15-20 seconds flash charging at every third or fourth bus stop;
- DFS (Depot Feeding station), 15-60 minutes slow charging.

A. Typical journey duty cycle

The typical operation and duty cycle of the TOSA bus during one day is the following:

- Leaving from depot in the morning (without passengers): start from bus depot with on-board energy storage fully recharged; drive to the terminal station; recharge completely the on-board energy system (by TFS).
- Cycling during operation (with passengers picked up at terminals and bus stops): drive between both terminals with partial intermediate recharges at some of the bus stops along the route (by FFS); recharge completely at each terminal the on-board energy system (by TFS).

- Returning to the depot in the evening (without passengers on board): drive to the depot without intermediate recharging; refill at depot (from a DFS at the overnight parking place or from a TFS at the entrance to the depot and then going to the overnight parking place).

B. Charger technology

Differently from the first demonstrator, the *Terminal* charger of TOSA Line 23 now consist of an insulated gate bipolar transistor (IGBT) based rectifier. This converts the incoming AC supply to DC in a similar way as is done for DC railways, trams or trolleybuses. However, the IGBTs provide the advantage of being able to maintain the output voltage at a desired level independent of fluctuations in the voltage on the AC network. This is important for two reasons. Primarily because the on-board battery chargers need to step up the voltage to charge the batteries and so, the voltage provided on the wayside cannot be higher than the on-board battery voltage. Secondly the voltage cannot be too low because then the current drawn would be too high for the required power.

The *Flash* charger uses the same type of IGBT charger as the terminal but it has a lower power capacity. Its function is to regulate the amount of charging current flowing into the wayside batteries. When the bus connects, the flash- stations' controller closes a contact on the output side of these batteries to discharge them into the on-board batteries. During the operation, the in-board batteries receive further top-up charges as the bus brakes. Rather than using a friction-based system that converts all the kinetic energy to heat, the buses' motors can switch to generator mode and return much of this energy to the batteries. The battery state of charge for a typical trip is shown in Figure 2. The graph shows how the batteries are topped up at bus stops but a far larger charge is received at terminals.

There is a third type of charger, for the *Depot*, where a longer charge is applied to compensate the energy required between the operating line and depot location. As there is more time for charging at the depot a flash-charging station is not required and power rating can be lower. A total of four buses can be connected to a depot charger, which charges them sequentially. The bus connects using its automatic connection system as it does along the route. This together with the logic programmed into the depot feeding station "wakes up" each bus in line for charging and then puts them back into "sleep mode" once the charge is complete. This saves energy without requiring depot staff to monitor the charging procedure. The electrical configuration is a simple but reliable 12-pulse diode rectifier as commonly used for railways; however, the power rating of the depot is a mere 45 kW avoiding the need for costly electrical infrastructure in the depot.

IV. Improved System performance

Based on the experience gained from the first TOSA demonstrator, the project that will run on TPG's Line 23 in Geneva will benefit from technical progress on the vehicle as well as on the infrastructure. For instance:

- The recognition of the infrastructure type and automatic equipment of the connection arm enables an increased amount of information for the infrastructure and independence of SAEIV (passenger information and operational support system);
- The infrastructure footprint is reduced through using higher energy density lithium titanate batteries used as opposed to double layer capacitors;
- The medium-frequency IGBT technology used in the charger reduces harmonics on the network and also the charger size;
- Permanent magnet motor vs asynchronous for the demonstrator. Less maintenance, less noise and better efficiency;
- New traction converter platform: less weight and improved efficiency.

A. Monitoring and analysis of power quality

Power system harmonic analysis on the demonstrator allowed to bring significant improvement on the harmonic contamination that terminal charging stations of the demonstrator had on the electrical grid. They have suggested replacing the 12-pulse diode rectifier of the Terminal Charging Station with an active front-end converter to eliminate low order current harmonics and achieve a unity power factor operation. An assessment has been performed to evaluate the harmonic content of the first terminal charging station – based on 12 pulse diode rectifier – on electrical grid due to the high amount of low-frequency harmonics because of a passive diode rectification.

B. Harmonic assessment for a TFS 12-pulse diode rectifier

After having gathered the data of the installation together with the grid data of the local utility (Services Industriels de Genève), this assessment has been performed following the DACHZ standard in three steps:

1) Power Ratio calculation: the ratio of short-circuit power S_{kV} at the low voltage point of common coupling to connected load of the installation of the network user S_A shall satisfy the following

$$\frac{S_{kV}}{S_A} \geq 150 \qquad (1)$$

where: S_A = 435 kVA

2) Harmonic Load Content: besides the new harmonic sources to be connected, the harmonic load S_{OS} of the installation of the network user also comprises those harmonic loads already existing. For a diode rectifier with a pulse number ≥ 12 a factor 0.5 applies

$$S_{OS} = 0.5\ S_A = 217 \text{ kVA} \qquad (2)$$

3) Evaluation of the Harmonis Load Content: the evaluation of the installation of the network user with regard to harmonics is performed using the diagram shown in Figure 3 and marking a specific point on it.

The point is calculated using the values of power ratio S_{kV}/S_A and the harmonic load content S_{OS}/S_A. The point on the graph also depends on the voltage level of the point of common coupling, which in this case is a 400 V (low voltage). If the marked point lies in the area below the curve, no remedial measures are necessary.

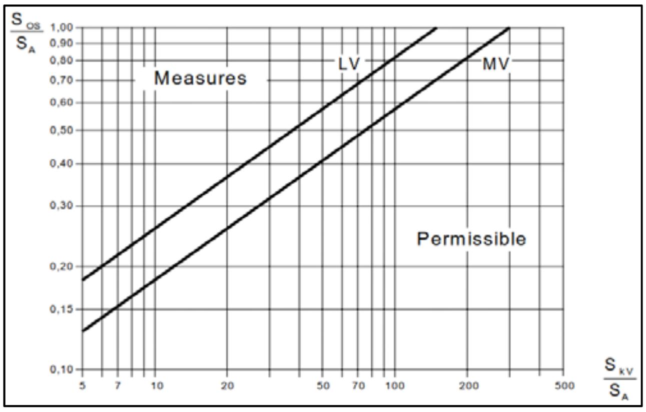

Figure 3. Diagram for the evaluation of the harmonic load content [1]

The network data and the results are shown on Table I and Figure 4.

TABLE I. NETWORK DATA AND CALCULATION RESULTS

Item	*Data*
Nominal Voltage	400 V
Short Circuit Power (S_{kV})	6.81 MVA
Maximum Power (S_A)	435 kVA
Current (I_A)	627.9 A
Repetition Rate	0.1-1 / min
Voltage Drop	2.33 %
Maximum Admissible Voltage Drop	3 %
Maximum Admissible Power	559.36 kVA
Power Ratio	15.66
Mimimum Admissible Power Ratio	150
Harmonics content	0.5
Maximum Admissible harmonic content	0.3

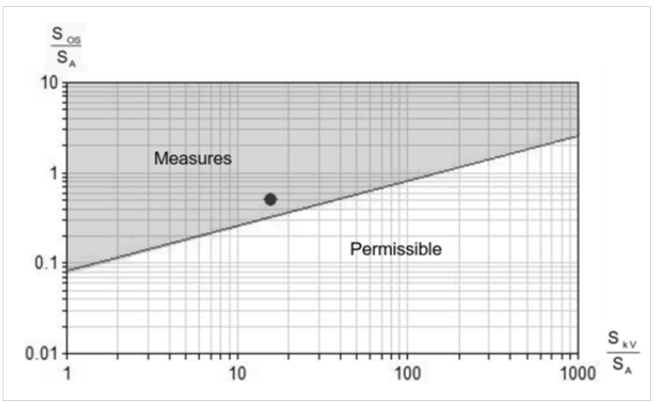

Figure 4. Diagram of the harmonic load content for a 12 pulse rectifier bridge at Terminal (TPG Line 23), 435kVA

As the marked point lies in the area above the curve, both terminal feeding stations of TOSA Line 23 will be equipped with medium-frequency IGBT technology helping reducing the harmonic content on SIG network.

V. IDENTIFY THE RIGHT APPROACH WITH A COST-OPTIMISATION TOOL

While it is understood that the concept of electric bus, able to charge its batteries at stops, is clearly an innovation, one of the main scientific and technological objectives of the TOSA project were to ensure the implementation of the concept to a real public transportation system as a viable, practical alternative to the existing transportation system using diesel buses.

ABB has developed an optimisation tool for cost-optimal deployment of an e-bus line to help cities in the process of finding the optimal concept for individual lines or complete bus networks.

It integrates different mathematical models. With the help of a simple and intuitive interface, the user enters the different parameters such as characteristics of the bus fleet and its components, their traction and auxiliary power consumption, the road profile, the timetable including the layover times at the terminal stations and depot, the location and some characteristics of grid connection points at charging stations. Tariffs and charges for consumers vary based on voltage level, power quality, time-of-day and peak duration.

The tool simulates the entire system and provides assistance while designing the system and, in addition, it shows the system performance in terms of energy and cost.

Apart from optimal placement of the “right” infrastructure at the “right” location to ensure the feasibility of transport operations, it is also required to optimise the overall day-to-day operational costs. One of the main cost parameters relates also to the amount of energy drawn from the grid utility. While the energy distributor might employ time-based differential pricing for drawing energy based on a pre-defined contract, the bus operators need to evaluate the costs associated with the different options and the timing to draw power so that the costs remain at the minimal.

VI. CONCLUSIONS

TOSA is the world’s fastest flash-charging connection technology taking less than 1 second to connect the bus to the grid. The onboard batteries can then be charged in 15 seconds with a 600 kW boost at the stop. The charging time is so quick that it does not interfere with the bus schedule and the lack of overhead lines improves the urban environment while providing greater route flexibility. A 3 to 4 minute charge at the terminals enables a full recharge of the batteries. This innovation won the prestigious German EBUS Award in 2014.

TOSA is a project comprising four partners, each of them providing core competencies with a single goal to explore, develop and demonstrate new possibilities for zero-emissions and sustainable urban mass transportation.

OPI: The Office for the Promotion of Industries and Technologies mission is to stimulate the development of industrial companies in the region by providing business support, notably on new and emerging markets.

TPG: The Transports Publics Genevois (TPG) are the leading transport operator in the France-Vaud-Geneva metropolitan area. It contributes to managing mobility across the region by proposing a quality service that respects principles of sustainable development. In all its activities, TPG seeks to ensure service excellence for the general public. It operates within the framework of a service contract renegotiated every four years with the Canton of Geneva.

ABB: (ABBN: SIX Swiss Ex) is a pioneering technology leader in electrification products, robotics and motion, industrial automation and power grids, serving customers in utilities, industry and transport & infrastructure globally. Continuing more than a 125-year history of innovation, ABB today is writing the future of industrial digitalization and driving the Energy and Fourth Industrial Revolutions. ABB operates in more than 100 countries with about 132,000 employees.

SIG: SIG is an essential part of everyday life for the people of Geneva, supplying them with water, gas, electricity and thermal energy. With its strong commitment to sustainable development, SIG recycles rubbish, treats waste water and provides innovative services in the telecoms and utilities sectors.

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