NEW TECHNOLOGIES FOR POWERING PUBLIC TRANSPORT VEHICLES

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***Abstract* – This paper provides a review of the new technologies being developed for electric urban public transport, which respond to the demand of removing the outside power lines, especially in some areas of the cities that constantly attract tourists. These technologies have been tested since the mid 1800's, in Washington and Budapest, but the modern versions appeared in late 2003, Bordeaux being the first city where it has been applied an innovative power system. This was a success and many cities followed this example and demanded from the electric public transport vehicles' producers alternatives to the old fashion power systems. The result was the development of electric transport systems that not only satisfy the primary aesthetic requirement, but are also less energy consuming, as they implement energy efficient methods, such as braking energy recovery. The reduction in consumed power leads to less impact on the environment, which is a necessity of nowadays. The technologies presented in this article are among the best to help providing future modalities for building more environmental public urban transport.**

Keywords: *energy, environment, electric public transport, supercapacitor.*

1. INTRODUCTION

The electrical public surface transport system is formed, in most of the cities, by trams and trolleybuses. This is an efficient mean of transport, especially compared with buses, but it also presents a big disadvantage: the necessity of catenaries to support the contact line for the electrical power needed. In the past years there was a growing concern about the cities' aspect being affected by these elements, and in order to keep the landscape clean of non-aesthetic elements, the demand for the public transport vehicle developers to find new power methodologies appeared. In this paper some modern solutions are presented, such as:

- APS[1] – which is a power supply system that makes use of a third rail embedded in the tracks;
- Battery packing – represents an autonomous on-board solution that allows the tram to operate in urban areas without overhead cables over distances under one kilometer;
- The inertia flywheel - stores kinetic energy generated by braking and releases it overhead sections with the sections without the overhead of over one kilometer,
- Sitras HES[2] - a system that enables the storage of the braking energy and the operation without overhead contact line; this system uses a mobile energy storage unit that enables energy-saving operation;
- Sitras SES[3] – another type of energy storage system.

In addition, due to the requirement for most European countries to reduce their carbon emissions and earn green tags has even driven those to open up mainline networks for electrification. Western European countries have rolled out programs to further electrify their rail networks to cope with mounting rail traffic. The high energy efficiency of electric rail addresses energy security issues and offers additional benefits of non pollution, faster acceleration and effective land utilization.

Expert analysts from modern research institutes currently take into consideration the following technologies: overhead lines, third rails, rigid catenaries systems, contact-free electrification systems and advanced conductor rail.

2. TECHNOLOGIES

2.1. APS

APS is a system designed to power trams without overhead catenaries, allowing the tram to operate "wire-free" over journeys of any distance and hence to blend into the urban environment.

Ground-level power supply, also known as surface current collection and APS is a modern method of third-rail electrical pick-up for street trams. It was firstly developed for the Bordeaux tramway, which was constructed starting with 2000 and opened in 2003. The system is shown in Figure 1.

[1] Alimentation Par le Sol – near-ground power supplying

[2] Hybrid Energy Storage System

[3] Siemens Energy Storage

Figure 1. Rail with APS system

Ground-level power supply is used, primarily for aesthetic reasons, as an alternative to overhead lines. It is different from the conduit current collection system which was one of the first ways of supplying power to a tram system by burying a third and fourth rail in an underground conduit between the running rails. Conduit current collection was used in historic tram systems in Washington for around 100 years, between 1862 and 1962. It fell into disuse because overhead wires proved to be much less expensive and troublesome for street railways.
Unlike the track-side third rail used by most metro trains and some main-line railways, APS does not involve a danger to living beings, so it can be used in pedestrian areas and city streets.

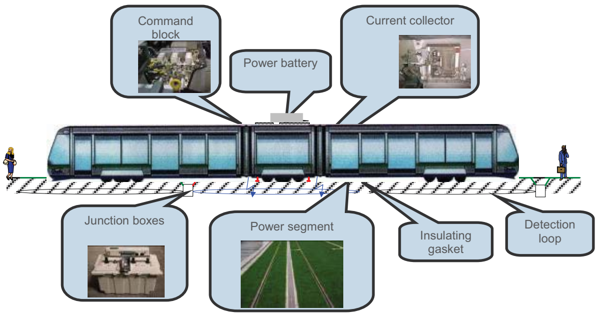

Figure 2. APS system

Power is supplied to the tram through a third rail embedded in the tracks. This third rail is made up of 8 meter-long conducting segments, which can be powered, and which are separated by 3 meter insulating joints. Power is supplied to the conducting segments by underground boxes every 22 meters. The electricity transmitted through this third rail is picked up by two friction contacts located in the mid-section of the tram. The delivery of power to the conducting segments is triggered by coded radio dialogue between the tram and the ground, *and only occurs once the conducting segment has been covered by the tram*, which represents the novelty of the system, ensuring total safety for pedestrians. The components of APS system are presented in Figure 2.

2.1.1. APS Implemented in World-Wide Cities

The Bordeaux Metropolitan Area is the first city in the world to have decided for this completely new technology on 14 km of its 44 km long tram network. It has been operating since the end of 2003 (you can see the tram powering from the third rail in Figure 3). The French transport administration chose an APS solution in 2006, like the Emirates of Dubai in 2008. A new generation of APS, APS_2, is being developed and can be adapted for both high level of humidity and heat.

2.2. The Battery Supply System

Another solution was implemented in Nice, where the usage of battery packs was chosen. The power supplying by batteries allows tram to cross distances up to one kilometer, area where the aerial contact wire is eliminated.

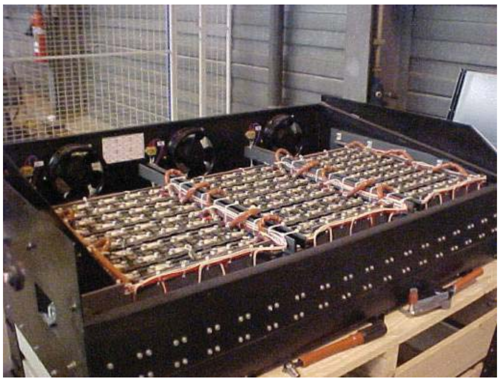

Figure 3. Battery pack

The demand here was for the tram to pass thru public markets, with lengths extending from 400 m to 1000 m without the presence of an overhead power line. The tram is in commercial service since 2007, the solution adopted being the usage of packs of NiMH batteries.

2.3. Supercapacitors

Capacitors store the electrical charge. Because the charge is stored physically, with no chemical or phase changes taking place, the process is highly reversible and the discharge-charge cycle can be repeated over and over again, virtually without limit.
Electric double-layer capacitors, also known as super-capacitors, pseudo-capacitors, electrochemical double layer capacitors (EDLCs), or ultra-capacitors, are electrochemical capacitors that have an unusually high energy density when compared to common capacitors, typically on the order of thousands of times greater than a high capacity electrolytic capacitor. For instance, a typical D-cell sized electrolytic capacitor will have a capacitance in the range of tens of mF. The same size electric double-layer capacitor would have a

capacitance of several farads, an improvement of about two or three orders of magnitude in capacitance, but usually at a lower working voltage.

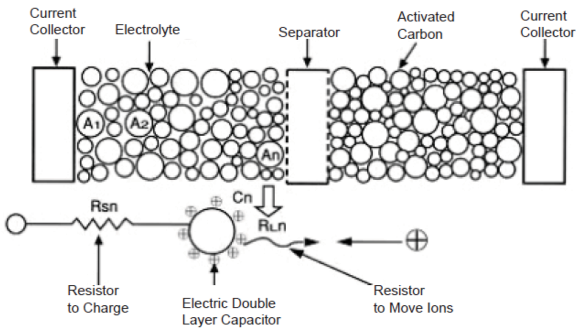

Figure 4. The structure of a supercapacitor

Whereas a regular capacitor consists of conductive foils and a dry separator, the super-capacitor crosses into battery technology by using special electrodes and some electrolyte. There are three types of electrode materials suitable for the super-capacitor: high surface area activated carbons, metal oxide and conducting polymers. The high surface electrode material, also called Double Layer Capacitor (DLC), is less costly to manufacture and is the most common. It stores the energy in the double layer formed near the carbon electrode surface.

This energy density of a super-capacitor is high in comparison to a regular capacitor but reflects only one-tenth that of the nickel-metal-hydride battery. Whereas the electro-chemical battery delivers a fairly steady voltage in the usable energy spectrum, the voltage of the super-capacitor is linear and drops evenly from full voltage to zero volts. Because of this, the super-capacitor is unable to deliver the full charge.

Because of their ability to rapidly charge, large super-capacitors are used for regenerative braking on vehicles. The charge time of a super-capacitor is about 10 seconds. The ability to absorb energy is, to a large extent, limited by the size of the charger. The charge characteristics are similar to those of an electrochemical battery. The initial charge is very rapid; the topping charge takes extra time. Provision must be made to limit the current when charging an empty super-capacitor.

The super-capacitor can be recharged and discharged virtually an unlimited number of times. Unlike the electrochemical battery, there is very little wear and tear induced by cycling and age does not affect the super-capacitor much. In normal use, a super-capacitor deteriorates to about 80 percent after 10 years.

The self-discharge of the super-capacitor is substantially higher than that of the electro-chemical battery. Super-capacitors with an organic electrolyte are affected the most. In 30 to 40 days, the capacity decreases from full charge to 50 percent. In comparison, a nickel-based battery discharges about 10 percent during that time.

Type EDL supercapacitors have a useful lifetime that decreases with increasing operating temperature, humidity, applied-voltage, current and backup-time requirements.

Expected lifetime is the product of four factors:

Expected Life = (Lifetime) x (Temperature Factor) x (Voltage Factor) x (Moisture Factor), where:

- *Lifetime:* The minimum rated life at 85 ºC with 5.5 V_{dc} applied is 1000 hours with maximum permitted end-of-life change of –30% capacitance and a 4 times increase in internal resistance.
- *Temperature Factor*: To determine the effect of temperature on expected life of a supercapacitor, use the fact that expected lifetime doubles for each 10 ºC that the operating temperature is reduced. As an illustration, at 85 ºC and full voltage the rated lifetime is 1000 hours. So, at 40 ºC the expected lifetime would be multiplied by 2(85-40)/10 = 24.5 = 22.6 times. The Temperature Factor is 22.6, and for 1000-h, 85 °C rated life, the expected 40 °C life would be 22600 hours.
- *Voltage Factor*: The rate of change of capacitance decreases with decreasing applied voltage. The effect on life extension is roughly proportional to the voltage derating, e.g., 5 V applied to 5.5 V rated supercapacitors extends the life 1.1 times.
- *Moisture Factor*: Expected life of these supercapacitors is considerably shortened by operation in high humidity. The applications discussed here assume that the relative humidity is no more that 50%.

In the following table is presented a comparison between different energy storage elements.

	Capacitors	EDLC	Batteries
Energy density [Wh/kg]	0.1	3	100
Power density [W/kg]	10^7	3000	100
Time of charge [s]	10^{-3} - 10^{-6}	0.3 - 30	> 1000
Time of discharge [s]	10^{-3} - 10^{-6}	0.3 - 30	1000 – 10000
Cyclability [1]	10^{10}	10^6	1000
Typical lifetime [years]	30	30	5
Efficiency [%]	>95	85 - 98	70 - 85

Table 1. Storage component property comparisons

2.3.1. Sizing a Supercapacitor bank

In order to obtain higher voltages and proper energy storage capacity, it is necessary to connect supercapacitors in banks, in series and parallel combinations. The huge energy stored in the supercapacitors is unable to distribute to a load due to its large equivalent series resistance, peak power is mainly limited by joule losses in the equivalent series resistance of the supercapacitors. When it is applied to large power density discharge, dynamic equivalent series resistance and ultimate discharge ability of supercapacitors is the dominating factor.

The maximum energy stored in the supercapacitor bank depends on its equivalent capacitance C_{eq}. The expression for maximum energy storage can be represented as following:

$$E_{max} = \frac{C_{eq} \times U_{max}^2}{2} \quad (1)$$

Where:

- E_{max} - the maximum energy storage capacity,
- C_{eq} - equivalent capacitance of supercapacitor bank in Farad,
- U_{max} - maximum voltage of the supercapacitor bank.

Practically it is not feasible to allow the supercapacitor bank to discharge all this energy therefore minimum allowable voltage limit is fixed that limits available energy. The discharge voltage ratio for the supercapacitor bank is represented as following:

$$\%d = \frac{U_{min}}{U_{max}} \times 100 \quad (2)$$

Where

- %d is percentage discharge ratio,
- U_{min} - minimum allowable voltage limit,
- U_{max} - maximum voltage of the supercapacitor bank.

The Depth of Discharge can be expressed as following:

$$DOD = (100 - d) = 100(1 - \frac{U_{min}}{U_{max}}) \quad (3)$$

DOD is measure of how much energy has been withdrawn from a storage device, expressed as a percentage of full capacity.

In power controlled operation mode it is necessary to maintain the minimum voltage so the required power can be discharged, therefore minimum discharge voltage can be represented by following expression:

$$U_{min} = R_{eq} I_D = \sqrt{R_{eq} P_D} \quad (4)$$

Where

- U_{min} - minimum discharge voltage permitted in volt,
- R_{eq} - equivalent series resistance of supercapacitor bank in ohm,
- I_D - discharge current in amp,
- P_D - discharge power in kW.

The maximum power that can be withdrawn from the supercapacitor bank and can be expressed:

$$P_{Dmax} = \frac{U_{max}^2}{4R_{eq}} \quad (5)$$

Where

- P_{Dmax} - maximum dischargeable power,
- U_{max} - maximum voltage of supercapacitor bank,
- R_{eq} - equivalent series resistance of supercapacitor bank in ohm.

Once the voltage constraints have been obtained i.e. $U_{min} < U < U_{max}$ then the useful energy that the supercapacitor bank can provide can be expressed as following:

$$E_u = \frac{C_{eq}(U_{max} - U_{min})^2}{2} \quad (6)$$

Above can be expressed in term of depth of discharge:

$$E_u = E_{max}[1 - (d/100)^2)] \quad (7)$$

Therefore the total capacitance of supercapacitor bank can be expressed in term of useful energy and maximum voltage:

$$C_{Teq} = 2\frac{E_u}{U_{max}^2[1-(d/100)^2]} \quad (8)$$

Here it is important to consider the efficiency of the supercapacitor bank which would finally decide the number of cells to be connected in series to obtain the maximum voltage of the bank and energy storage capacity of the bank.

2.3.2. Application in Public Transport

EDLCs have a variety of commercial applications, notably in "energy smoothing" and momentary-load devices. They have applications as energy-storage devices i.e. in public transport vehicles, where extremely fast charging is a valuable feature.

The super-capacitors are installed in a casing on the tram’s roof. When the tram stops at a station to load or unload passengers, the tram’s pantograph is raised and power is supplied via the overhead contact line to recharge the super-capacitors. The tram can then continue running without catenaries since it is powered by the super-capacitors during the traction stage and is able to recover the energy produced during braking stages; the onboard energy supply enables autonomous travel between stations. This system can reduce the tram’s energy consumption by up to 30%.

Advantages of super-capacitors in public transport:

- preservation of urban landscape;
- energy autonomy between stations;
- energy savings up to 30%;
- less drain of electrical substations;
- no additional ground infrastructure.

China is experimenting with a new form of electric bus (*Capabus*), that runs without power lines using power stored in large onboard electric double-layer capacitors, which are quickly recharged whenever the bus is at any bus stop (under so-called electric umbrellas), and fully charged in the terminus. A few prototypes were being tested in Shanghai in early 2005. In 2006, two commercial bus routes began to use electric double-layer capacitor buses; one of them is route 11 in Shanghai.

In 2001 and 2002, VAG, the public transport operator in Nuremberg, Germany tested a hybrid bus which uses a diesel-electric battery drive system with electric double layer capacitors.

Since 2003 the public transport in Mannheim, Germany has operated an LRV (*Light-Rail Vehicle*) which uses electric double-layer capacitors to store braking energy.
Other companies from the public transport manufacturing sector are developing electric double layer capacitor technology, a mobile energy storage based on double layer capacitors, a stationary version integrated into the trackside power supply. Other companies are also developing an electric double-layer capacitor-based energy storage system.
It has also been created the world's first triple hybrid Forklift Truck, which uses fuel cells and batteries as primary energy storage and electric double layer capacitors to supplement this energy storage solution.

2.4. The Inertia Flywheel System

The *inertia flywheel* - allows the tram to generate its own completely renewable power by recuperating the energy produced during braking. The inertia flywheel, tested under real-life operating conditions since 2005 on a tram in Rotterdam, innovates through its use of electro-magnetic field. The system consists of a rotating mass positioned on the tram's roof, which functions like a spinning top. The kinetic energy stored during braking is then returned to the traction system at the next acceleration. The system is "charged" whenever the tram brakes or via an additional fast charging system at each station. The use of the energy stored on board therefore allows a considerable reduction in electrical power consumption, with a system lifetime that is equivalent to that of the tram itself.

2.5. Hybrid Energy Storage

2.5.1. German Solution

Siemens' energy storage system reduces emissions by up to 80 metric tons of CO_2 per year and enables trams to operate without an overhead contact line.
The Sitras HES[4] system, developed by Siemens, consists of a Sitras MES – a mobile energy storage unit - and a traction battery. "Trams with hybrid energy storage systems can operate without an overhead contact line (OCL) over distances of up to 2,500 meters. They not only preserve historical buildings and enhance the appearance of the urban landscape; they are especially environment-friendly and save energy", stated a representative of the company. Vehicles equipped with energy storage systems consume up to 30 percent less energy per year and produce up to 80 metric tons less CO_2 emission than vehicles without energy storage systems.
In Portugal, the hybrid energy storage system has been successfully used in passenger services since November 2008. It has also been certified according to the German Construction and Operating Code for Tramways, for use in the public transport.
The HES storage system consists of two energy-storing components: the MES unit (a double-layer capacitor) and a nickel-metal hydride battery. MES enables energy-saving operation. The HES hybrid concept combines the advantages of the DLC with the properties of a traction battery.
The systems are mounted on unused roof surfaces of a tram and electrically connected to the feed-in point of the vehicle by means of a DC/DC-chopper. Thanks to this new autonomous connection concept, the energy storage system can be directly integrated into new vehicles or built into ones that already exist. When the vehicle is in operation, the energy storage units are charged during braking, so a vehicle can use this stored energy to travel relatively long distances without having to be supplied with power from the contact line. The energy storage units can also be recharged on routes with OCLs or stationary charging stations, for example at stops. The high energy content of the traction battery also allows operation in case of an OCL-failure or maintenance work on the OCL as well as when unforeseeable problems arise on routes without OCLs.
By recovering the extra energy generated during braking, a vehicle equipped with HES or MES can reduce its energy demand in future by up to 30 percent under optimum operating conditions. Moreover, the line voltage becomes more stable because the voltage drop along the OCL is reduced, especially during peak hours. Driving without contact line is especially suitable where there are difficult built structures that complicate its installation, for example in tunnels, under bridges, at system changeover points or major intersections used by different transportation modes.

2.5.2 The System Design

The hybrid energy storage system can be directly integrated in new rail vehicles (integrated concept) or can additionally be installed at existing rail vehicles (independent concept).
Both storage technologies and both concepts for HES are approved according to the German construction and operating code for tramways.
The system employs an integrated concept:

- Phase module of the step-up/step-down chopper is integrated within the traction converter;
- Electrical connection to the intermediate DC-link;
- Closed-loop control embedded in the common control unit.

The figure 5 depicts the integrated concept of the hybrid energy storage technology. A battery of double layered capacitors is quickly charged from the overhead contact line or the braking system.

[4] HES – Hybrid Energy Storage

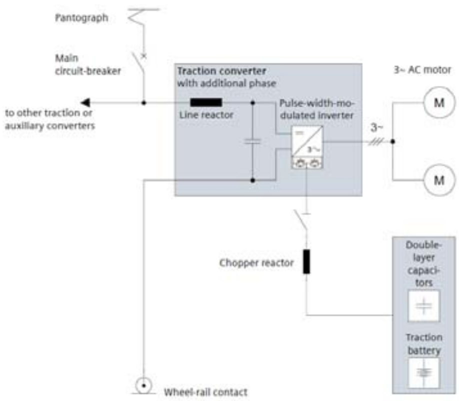

Figure 5. The integrated concept of HES

The technology also involves an independent concept:

- The step-up/step-down chopper is an independent unit;
- Electrical connection to the common feeding point of the rail vehicle;
- Independent control unit;
- The line reactor decouples the independent energy storage system.

This independency is showed in figure 6.

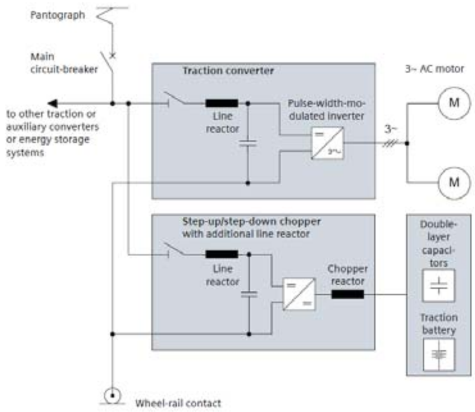

Figure 6. Independent concept of HES

2.5.3. The Energy Storage System

SES[5] is permanently integrated into the traction power supply system. There for, excess energy that has been recovered within a network, e.g. from braking, is temporarily buffered and released again when required.

SES has been successfully installed in numerous mass transit systems. Two operating modes are available. On the one hand, SES can be used as a temporary buffer store. The energy recovered when the vehicles are in braking mode is stored and made available for subsequent use. Depending on the system, up to 500,000 kWh of the primary energy requirement can be saved, corresponding to almost one-third of the annual consumption.

SES also acts as a voltage stabilizer, especially during traffic peaks, to prevent the line voltage from dropping below a critical level.

[5] SES – Siemens Energy Storage

3. CONCLUSIONS

The implementation of these systems could represent a major improvement in the electrical transport field. To take an example, the public transport operator in Bucharest currently needs about 12,000 MWh each month, just for their electrical transport. Computing the energy consumed in a year, this is 144,000 MWh. Taking into account the estimates mentioned in this article, an implementation of new technologies on the entire electrical fleet would lead to a reduction of about 43,200 MWh. This is really impressive, considering that an average household is estimated to consume about 10MWh a year and therefore the reduction of energy consumption achieved by only one public transport operator (true, the biggest in Romania) could power up all the households in a small city.

So, although these systems were designed at first to meet an aesthetic demand, they proved to be a high-quality reliable solution not only by the preservation of urban landscape and the reduction of costs with the infrastructure but also by achieving a diminished energy consumption which is making the electrical surface public transport even more environmental – friendly and turns it into the most suitable solution for the future.

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