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Analysis of regenerative braking and energy storage systems in urban rail transportation

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A B S T R A C T

Energy saving on urban rail systems has been studied for many years and the major parameters affecting energy consumption are defined as the driving strategy, regenerative braking and energy storage systems. In this study, the factors influencing energy consumption is analyzed and innovative solutions are extensively reviewed. The present paper reports the main results of analysis and giving some suggestions about possible energy saving actions in electric power system. Lastly, the advantages of current energy storage systems are stated.

1. Introduction

Nowadays, especially in big cities, public tendency for using electric underground railway systems (metro) instead of other transportation vehicles is increased depending on heavy traffic in highways, environmental factors and high fuel cost. According to the researchers, electric railway transportation companies are the main consumers of electrical energy in their regions. Even though railway is more energy efficient than most other transport modes, the enhancement of energy efficiency is an important issue for railway operation to reduce their contributions to climate change further as well as to save and enlarge competition advantages involved. Therefore, most of the transportation companies are integrating regenerative braking technologies and energy storage systems (ESS) into urban rail operation [1,2].

The regenerative braking is an important control technology of DC metro trains that reduces train speed by converting some of its kinetic energy into current instead of dissipating it as heat as with a conventional brake. The ratio of modern trains with regenerative braking function has been increased in the latest years, and electric railways need new strategies both in electrification and train controls in order to take advantages of braking energy recycling effectively [3,4].

The energy consumption depends on various parameters as operation frequency, acceleration and deceleration rate and the weight of metro trains. Efficient operation of the railway system is considered as the key feature of energy saving. Low acceleration and braking rates both reduce the energy consumption level but these applications extend the period of the journey. Besides this, other methods affecting energy saving in urban rail transportation is analyzed and discussed.

The energy-saving technology for urban railway is mainly focused on carrying out the braking enegy recycling with the use of inverter technology and various energy storage devices (super-capacitors, fly-wheel, hydraulic devices, etc.). Although different technical solutions are proposed and substantial research has been done, there are still many important problems that need to be addressed further.

The energy storage system creates optimum conditions for energy regeneration in urban mass transit system. The energy storage system must be able to store and discharge energy extremely quickly, consequently enabling a complete exchange of energy between vehicles, even if they are not braking and accelerating at precisely the same time, as is most frequently the case in everyday service. The energy storage system reduces primary energy consumption without affecting transport capacity and punctuality. In addition, the energy storage units can stabilize the system voltage. The energy storage system must be developed to use regeneration energy when the vehicle is braking [5].

Due to periodic acceleration and deceleration as trains move from station to station, their power consumption is very uneven. Therefore, electrically powered railway systems such as trams, subways, and high-speed magnetic levitation trains can benefit from electric energy

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storage to smooth out the train power demand. Energy storage systems can be installed either at the substation supplying the train network or on the train itself. In addition, when placed at the substation, energy storage systems can serve as peak-shaving units or as demand-flattening units.

2. Regenerative Braking Energy

Regenerative braking is any technology that allows a vehicle to recapture and store some part of the kinetic energy that would ordinarily be lost when braking. It is an energy recovery mechanism which slows a train by converting its kinetic energy into another form, which can be either used immediately or stored until needed. Electric railway vehicles feed the recaptured energy back into the grid, while road vehicles store it for re-acceleration using flywheels, batteries or capacitors. Older dynamic brake systems generally used the electricity to provide heat or just passed it through large banks of resistors to dissipate the energy.

In principle, dynamic braking, as the engine will work as a generator during braking, the kinetic energy is transformed to heat affecting the braking resistances. The most common form of regenerative brake involves using an electric motor as an electric generator. In electric railways the generated electricity is fed back into the supply system, whereas in battery electric and hybrid electric vehicles, the energy stored in a battery or bank of capacitors for later use.

The two main reasons to employ regenerative braking are energy saving and reduced wear of mechanical brakes. The technique of regenerative braking is most effective in full stop passenger trains and subway (metro) trains, because they stop often enough to make recovery worthwhile. The rate of regenerated energy usage can be increased with synchronizing of departing and arriving trains in a station [6,7].

Many newer electric railway cars couple a regenerative braking system with a mechanical one. Their operation is similar in nature to a dynamic braking system where the traction motors are turned into generators. The difference is that with regenerative braking systems the current from the traction motors is sent to the trolley wire through the pantograph. When electric regenerative braking is implemented in the trains, the energy coming from this braking process cannot always be used for another trains and therefore it have to be eliminated in electric resistances (rheostatic braking).

In the regenerative braking system, the braking controller is the heart of the system because it controls the overall process of the motor. The functions of the brake controller are monitor the speed of the wheel, calculate the torque, rotational force and generated electricity to be fed back into the energy storage system. During the braking operation, the brake controller directs the electricity produced by the motor into the batteries or capacitors.

3. The Factors Affecting Energy Efficiency

The electric supply system has a considerable influence on the feasibility of energy recovery. There are a number of traction electrifications with different voltage levels in DC systems around the world, such as the 600V, 650V, 750V, 1500V and 3000V. In DC systems, the catenary can be interconnected over great distances (since in contrast to AC systems, no phase shifts can occur). This would in principle allow for a long-distance transmission of recovered energy. However, given the low voltage of these systems (1,5 or 3 kV), transmission losses strongly limit the feasible feeding distances.

The level of energy available to be recuperated depends on the railway network and its receptivity capability, or its capacity to absorb excess energy. Many operators are faced with this dilemma and have to install resistors that will be connected to the network when this energy is detected, where it will be dissipated in heat. This amount of energy can amount to large numbers, and if stored and re-used, could generate important energy savings.

Activation of stationary and on-board energy storage systems during construction will also provide significant energy efficiency. Automatic driving systems depending on the density of passengers will also provide significant energy saving by affecting the operation frequency rate of metro trains.

Apart from energy needed for train motion, passenger trains consume energy for comfort functions. This energy can reach about one fifth of the total energy consumption of a train during service. Since air-conditioning (heating in winter and cooling in summer) accounts for the biggest share of comfort energy, the total demand for passenger comfort highly depends on the region and season.

Energy consumption can be measured most effectively by means of energy meters installed on trains. They allow for an exact monitoring not only of energy intake, but also of recovery rate (by regenerative braking). Energy meters are also an essential condition for energy billing, an issue gaining growing importance in liberalized railway markets. Only if private train operators have to pay for the energy actually consumed rather than a system average, they do have an incentive to use energy efficient stock or apply regenerative brakes.

Instead of measuring the energy actually consumed in service, one can calculate the demand with modern simulation tools. The results may be collected in a database of traction consumption in order to provide relevant data for a number of purposes including timetable planning and determination of ideal train constellations.

4. Energy Storage Systems

In today's electric transit systems, capturing and regenerating the braking energy is rapidly becoming the key feature as reducing the overall consumption and greenhouse gas emissions. The kinetic (movement) energy of a train can represent up to 80 percent of the total energy consumption of a railway transportation system. Whenever a train brakes at a station, its kinetic energy is converted into electricity and returned on the traction power line. Most of the time, on-board loads and distant trains can only take a small portion of this energy, and the surplus is wasted into on-board or wayside resistors.

A wayside energy storage system shown in Figure 1 stores and recycles this surplus energy, can reduce the total energy consumption of a rail transportation system between 10-30 percent. The train braking event lasts only seconds yet it generates extremely large currents and can occur thousands of times each year. For these reasons, super capacitors represent an ideal and effective storage technology. The latest generation of double layer super capacitors captures this braking energy and return seconds later to assist the departure and acceleration of the train. The system captures and recycles only real surplus energy and rarely triggers on false events such as changes in acceleration.

Figure 1. A Wayside Energy Storage System for Rail Transportation

The proposed energy storage solution is based on a battery technology, used as the wayside energy storage device as shown in Figure 2. The system consists of one control module and two battery modules. The control module is the center point of all internal and external communication of entire system. The battery module consists of eighty 12V battery blocks, for a nominal voltage of 960Vdc. Connection to traction power grid is through a charge/discharge power converter, also referred to as a bi-directional DC-DC converter. The converter ensures that the batteries provide current even if the voltage is lower than the grid voltage.

Figure 2. Site View of the Energy Storage System and Battery Container

Recycling the braking energy is the single largest opportunity to improve the energy efficiency of rail transportation systems. A wayside energy storage system can provide additional benefits like fixing the low voltage problems that are often seen when service levels are increased or when new modern cars are introduced. These systems can also become an off-grid traction power supply. As such, they are precharged in-between train arrivals via either the traction power line or a small rectifier, and they capture the surplus braking energy. Such off grid traction power systems are less expensive and more energy efficient than traditional grid-connected traction power supplies (Figure 3). Finally, when coupled with optional batteries with larger energy reserves, the energy storage systems can also become a smart grid asset capable of providing frequency regulation or other demand response energy services to the local energy distribution company.

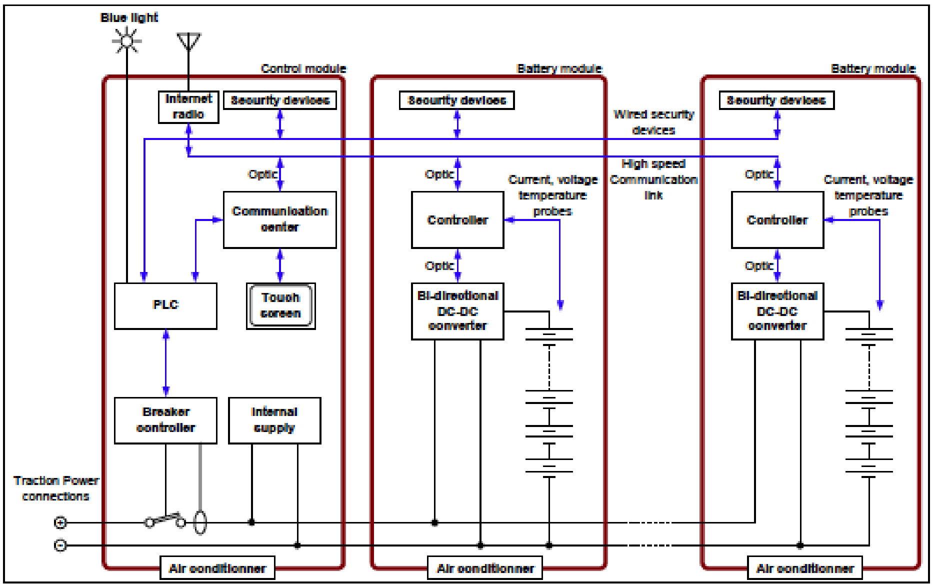

Figure 3. Battery Substation Block diagram

Identifying the correct battery technology for energy storage systems is a particular case. As there are many choices of battery technologies, selection had to be based on the application requirements. The most critical selection parameters are high discharge current, relative low initial cost and cost of replacement. Different battery technologies are therefore evaluated, based on these criteria, and the results are presented in Table 1.

Nickel Cadmium batteries probably offer the best all-around performance, but its cost is very high and the number of suppliers limited. Nickel Metal Hybrid batteries also offer interesting performance features, but again, its cost is prohibitive. Lithium Ion Phosphate technology offer very promising cost and feature parameters, but it is a fairly new technology with a limited amount of manufacturers. Although very popular in some applications, the Lithium Ion technology was not considered due to its higher internal resistance and therefore inability to provide high peak currents. Since the type of load application is unchartered territory for most of these technologies, it was felt that it was a great opportunity to verify the performance of sealed lead acid batteries in a high load cycling environment.

Table 1. Battery Technology Features Rating

	Price / Capacity	Discharge current	Energy / volume	Cycle life	Charge current
Nickel Cadmium (NiCad)	High	Very High	Medium	High	Low
Nickel Metal Hydride (NiMH)	Very High	High	High	High	Medium-low
Sealed lead-acid (AGM)	Low	High	High	Low	Low
Sealed lead acid (AGM, wound cell)	Low	High	High	Medium-low	Medium-low
Lithium Iron Phosphate (LiFePO4)	High	Medium-high	High	High	Medium

5. Conclusions

The recycling of the braking energy of trains causes significant electricity savings, environmental benefits and supplementary revenues. The major factors influencing the energy consumption are respectively the weight of the train, operating frequency and the maximum acceleration. Efficient operation of the railway system is considered as an essential way of energy saving in urban rail transportation.

Energy storage systems are the key enabling technologies for transport and utility applications. Mature storage technologies can be used in several applications, but in other situations, these technologies cannot fulfill with the application requirements. Thus, new storage systems have appeared, opening new challenges that have to be solved by the research community. Transport and utility applications operate with a wide range of time versus power storage requirements. The benefits obtained in transport and utility go from technical aspects to economic objectives.

The innovative designs allow the wayside energy systems to improve the energy efficiency of DC traction power grids. They reduce voltage drops that can occur in some areas of the distribution grid, which improves the performance of the trains and also operates off of the public energy grid and can store energy during off-peak periods and send it back during peak operation. As capturing excess regenerative energy on the traction power line, stores it, and returns it to the traction line when needed, reducing peak demand (peak shaving), helps reduce voltage drops on transit power systems, therefore improving transit performance.

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