Switching Locomotive as a Part of Smart Electrical Grid

Anton Rassõlkin, Hardi Hõimoja

Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia (Tel: +37253919587; e-mail: anton.rassolkin@tptlive.ee, hardi.hoimoja@epfl.ch)

Abstract: Today, the concept of smart electrical grids is well developed and becoming more popular. The main components of every single smart grid are the distributed energy generation and energy storage elements. The energy produced by the alternative energy sources (e.g. wind and solar plants), as well as regenerative elements (e.g. electrical braking), usually does not follow synchronously the consumption, meaning that energy storage devices are needed to balance the production and consumption. There are several different energy storage solutions available today. This paper presents a possibility how to integrate a diesel-electric switching locomotive with smart electrical grid and how to improve the efficiency of switching locomotive by using the modern energy storage devices.

Keywords: energy storage, efficiency, smart power applications, ancillary services

1. INTRODUCTION

The electric grid in its current form was developed a long time ago and in some cases needs a particular modification. An actual solution of electric grids upgrading is the Smart Grid (SG) conception. The main characteristics of a SG are:

- distributed energy sources;
- energy storage systems;
- advanced communications.

Today the power plants produce a huge volume of electricity and often transfer them over a long distance, which increase the energy losses. The idea of SG is to reduce the energy production of a single power plant and increase the number of local power plants. It makes the grid more distributed. The energy flow produced by alternative energy sources strongly depends on the sources themselves (solar panels, wind farms, wave energy), but not from the energy consumption. That’s why the energy storage systems (ESS) become irreplaceable in SG. The most widespread ESSs are presented in the paper. The development of electric vehicles (EVs) and hybrid-electric vehicles (HEVs) makes them an important part of SG. When EVs and HEVs are plugged-in to SG for charging, they could be used as ESS. This concept is called Vehicle to Grid (V2G). V2G is still new and under development now. By their fundamentals the diesel-electric locomotives are very close to series HEVs. This opportunity makes it possible to implement the locomotives to the SG systems as well. In this paper, a modification solution of switching locomotive ČME3 is proposed.

ČME3 is the mostly used type of switching locomotives in Estonia. The locomotives themselves are three decades old and the used technologies are even older. The Estonian railway is connected to European and Russian railroads which means the locomotives used in Estonia should correspond to both railways standards (Rassõlkin et al. 2011). From the economical point of view, modernization of ČME3 is advantaged.

2. ENERGY STORAGE APPLICATIONS

There are many different energy storage solutions available today. Some of them allow to store a large volume of energy for a quite long time (e.g. fuel tanks) and some of them can save energy just for a couple seconds (e.g. supercapacitors, SMES). The diagram in Fig. 1 shows the energy storage systems that can be possibly used to store energy in locomotives.

![Energy Storage Solutions](image)

Fig. 1. Energy management of energy sources used nowadays (Farret et al. 2006).

Fuel tanks are reservoirs that are used to store the fossil fuels. Diesel and petrol produced from the rude oil are the most common by used fuels in the world. Also natural gas and biomass can serve as fuel. The reason of using combustible fuels is simple, as huge volumes of energy could be stored in tanks for a long time with no additional efforts and losses. On...
the other hand, the fossil fuels have a list of disadvantages. To take out energy they should be combusted at first, which means huge heat losses, small efficiency factor and CO₂ emission. Moreover, to get electric energy the additional converter in form of generator is required, which significantly reduces already low efficiency factor of internal combustion engines (ICE).

A fuel cell is an electrochemical device that produces electricity by means of a chemical reaction, much like a battery. Fuel cells can produce electricity as long as fuel – usually hydrogen - is supplied, which means they also need some reservoirs to store fuel. Fuel cells that are used in commercial applications could be divided by different temperature ranges. First one with an operating temperature up to 250°C (Alkaline Fuel Cell, Proton Exchange Membrane Fuel Cell, Direct Methanol Fuel Cell, Phosphoric Acid Fuel Cell). They usually have low power range and less efficiency. The high temperature fuel cells, with an operating temperature higher than 600°C (Molten Carbonate Fuel Cell, Solid Oxide Fuel Cell) are mostly used in high power generation as they have higher efficiency and output power. The main benefits of fuel cells are – low zero emission, as the sole product of reaction is water; high electric efficiency up to 60 %; very simple construction. The only drawback of a fuel cell for today is its high price and limited technologies.

Batteries are well known assemblies electrochemical cells that convert stored chemical energy into the electricity. Different battery technologies are addressed to small portable applications, but there are some difficulties in using them in high-power applications, because of the high weight-power relation and self-discharge. The most common lead-acid batteries are used in renewable energy applications providing stand-by energy or working on regular basis in hybrid systems. The main benefits of the lead-acid batteries are: good efficiency; low maintenance level; easy installation and low investment price. The main drawbacks are - sensitivity to extreme operating conditions such as extreme temperatures and overcharging.

Different from usual batteries are advanced batteries. There is a wide range of advanced nickel batteries - nickel-cadmium (NiCd), nickel-metal-hydrate (NiMH) and nickel-zinc (NiZn). Good temperature operating range, low cost and high power output are the advantages of nickel batteries. The main applications for nickel batteries are automotive applications EVs and HEVs, railroad services, switchgear operation, telecommunications, emergency lighting and Uninterruptible Power Supply (UPS) systems. Different types of metal-air batteries have been developed in the last years including zinc-air, aluminium-air, magnesium-air, iron-air and lithium-air batteries. The main benefits of this type of batteries are: long shelf life; relatively low cost; capacity independent of load and temperature, when working within normal operation range. There are also some drawbacks such as: limited output power; low current density obtainable; limited operating temperature range. Zebra batteries operate at high temperature (250 °C ... 350 °C) and utilize molten sodium aluminiumchloride (NaAlCl₃). Due to the high energy density they are used in automotive and railway applications. The benefits of Zebra batteries are high efficiency; low self-discharge and the fact the cells being fully sealed and maintenance-free; discharge capacity is independent of the rate of discharge. The drawbacks are limited range of available sizes and capacities; high operating temperature; using ca 14% of its own capacity per day to maintain temperature when not in use; thermal management needed. The reduction-oxidation flow batteries (RFB) are the advanced ones in which the chemical energy is converted into electricity by the transmission of solid electro-active components through power cells. The main technologies of RFB are based on vanadium and bromine. The main benefits of RFB are no memory effect; no self-discharge; high power rating; long energy storage time; no degradation for deep discharge. Their drawbacks are limited temperature range and capacity limitation by number of ions in electrolyte.

Flywheel energy storage (FES) systems are electromechanical storage devices that store kinetic energy of a rotating body. FES consists of a rotating element with a large moment of inertia that keeps the torque for some time. Rotor is suspended by bearings; usage of magnetic bearings instead mechanical reduces the friction of the system and increases energy storage time. The kinetic energy stored in flywheel could be used as mechanical energy, or converted into electric one. FES can be used in different applications from network stabilization and network frequency regulation to energy stored elements in vehicles and even in UPS systems. The main benefits of flywheel are low price; fault-tolerance and durability; high efficiency factor. The drawbacks are short energy storage time; design limitations; high energy losses with mechanical bearings.

An electric double-layer capacitor (EDLC), or just supercapacitor is a capacitor with a high power destiny, with a capacitance up to kilofarads. In comparison with batteries the charging/discharging times of supercapacitors are significantly shorter, which makes them an ideal solution for the devices that use electric motors to smooth the start-up current and voltage peaks. The main benefits of supercapacitors are high specific power and high efficiency, low self-discharge, long life lifetime, low cost per cycle. The main drawbacks of supercapacitors are low voltage of single device; to increase the voltage several capacitors should be connected in series which decrease the total capacity.

Superconducting magnetic energy storage (SMES) is a device that stores energy in the magnetic field produced by direct current in the overcooled to cryogenic temperature coil. Since energy is stored as circulating current, it can be drawn from an SMES unit with almost instantaneous response within periods ranging from a fraction of a second to several hours (Hasan Ali Mohd et al. 2010). To reach the cryogenic temperature a liquid helium or nitrogen are usually used. The operating temperature used for a superconducting device is a compromise between cost and operational requirements (Hasan Ali Mohd et al. 2010). The main benefit of SMES is the extremely short charging/discharging time, which means the storage power is available almost instantaneously and high energy output can be reached. The main drawbacks are
very short energy storage time and the high price, the cryogenic temperature can be a challenge as well.

Nowadays the smart electric grid systems use some other energy storage systems, like water dumps, thermal reservoirs, compressed air systems etc. But their application in railways and other vehicles is a competition.

Because of environmental hazard and limited amount of fossil fuels there is a tendency in recent decades by replacing ICE vehicles by EV’s, HEV’s and fuel cell vehicles. That’s why the energy storage devices that do not pollute the environment are required. As it can be seen from the Fig. 1 such storage elements as supercapacitors, flywheels and SMES’s could save energy only for a few seconds, that limit their usage as a primary energy sources. But there are some solutions that do not need to cover long distances, and few-second acceleration is enough to reach the required speed of vehicle.

3. THE POSSIBLE MODERNIZATIONS OF ČME3

3.1 Construction of switching locomotive

By its structure the diesel-electric switching locomotive is close to series HEV. The diesel engine (DE) is mechanically linked to the traction generator (TG) that feeds the traction motors (TM). The battery (BAT) is required for running-up the DE and to feed the auxiliary circuits. The principle scheme of the diesel-electric switching locomotive ČME3 is presented in Fig. 4.

![Fig. 2. The principle scheme of the diesel-electric switching locomotive.](image)

For the DE a four-cycle water-cooled engine is used, with a rotating speed of 750 rpm and the rated power of 993 kW. For the TG the 10-pole separately excited DC generator is used. The electric energy produced by a DC generator is transferred to the six 4-pole series DC motors (TM) (Rassölklin et al. 2011). The TG is also used as an electric motor for soft starting the DE. The alkaline battery (Ni-Cd) with capacity of 150 Ah and voltage of 90 V is used. The mass of BAT is almost a ton.

3.2 Duty cycle of switching locomotive

The switching operations require the switching locomotives to work permanently in transient modes, with repeated take-offs and accelerations. The working mode of switching locomotives is presented in Fig. 3. These measurements were taken from switching locomotive over a period of one hour. The histogram in Fig. 4 gives a graphic impression of the working modes of switching locomotives. As it can be seen from the Fig. 3 and Fig. 4 in one random duty cycle the switching locomotive works almost all the time with less than half load in short periods and there are lots of power spikes that are incidental to run-up mode of locomotive’s traction system. All locomotive’s equipment should be protected from the influence of the run-up currents that usually increase the total price of equipment. To reduce the run-up currents influence the supercapacitors could be used, because of their ability to give back the huge energy flow in very short time is a perfect solution.

![Fig. 3. Working mode of switching locomotive.](image)

![Fig. 4. The histogram of switching locomotive’s working mode.](image)

3.3 Modernization of ČME3
The circumstance that the switching locomotive does not operate with full load discredits the use of diesel engines as a primary energy source. Moreover, the battery currently used in a locomotive has a low efficiency factor and is in use only when the locomotive is starting up. A principal scheme for possible modernization of ČME3 is presented in the Fig. 5.

![Fig. 5. Possible modernization of ČME3.](image)

One of the disadvantages of the currently used in ČME3 scheme (Fig. 2) is controlling the traction motors directly with a traction generator. If TM works with partial load, the huge flow of energy produced by TG disseminates. If there were a battery link between TG and TM, the energy flow between electric machines would be more controllable. The bidirectional power electronic devices (PE) would allow the energy flow on back direction. It means it would be possible to use the regenerative braking mode in TMs and store that energy. Using the supercapacitor link (SC) would reduce the spikes of running-up currents. The flywheel (FW) could store the kinetic energy that could be converted into electric one by using TG. In case the FW would be used, the additional mechanical clutch is required.

Adding the storage elements to locomotive traction system would complicate the control system. But on the other hand, advanced storage elements would improve the energy distribution of switching locomotive and the whole system could be considered as a micro grid. Integration of such Micro-Grid switching locomotive system to a smart electric grid would be possible.

4. CONCLUSIONS

The switching operations make the switching locomotives to work in an unsteady mode, with repeated take-offs and accelerations (Rassõlkin 2011). This fact designates some parameters of energy sources that could be used in switching locomotives. The energy flow produced by engine-generator set has a delay needed for diesel engine start. When such energy storage devices like batteries, supercapacitors and SMESs could provide electric energy immediately. Moreover, the energy generated by regenerative braking could be stored in these energy storage devices as well. Flywheel will give a possibility to store the kinetic energy and convert it into electricity.

Of course, it is impossible to totally neglect the fossil fuels, but with the development of fuel cell technology the usage of fossil fuels could be significantly reduced. In case of using two or more energy sources, the switching locomotive could work as HEV, use batteries for short-time switching operations and diesel engine to feed the batteries for mainline operations.

The modernization of locomotives will improve their life cycle. Economically it is always cheaper to service periodically than to buy a new locomotive (Rassõlkin et al. 2011). Moreover, it will produce the most striking instance of experience using new technologies, before installing them on new devices (Rassõlkin 2011). The operational efficiency of switching locomotive would be increased. Also such important electric grid parameter as power quality could be improved by applying the switching locomotive with modernized traction system to grid.

The locomotives modernization would also have a positive influence on the environment. It will decrease the fuel and oil consumption, reduce the CO₂ emission, as well as reduce noise produced by locomotive.

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