DC Railway Catenary Regulation Based on KESS

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1. INTRODUCTION

Energy consumption in transportation is a serious social problem. The increase of transport energy consumption is higher than in other energy uses (in Spain, railway has increased 6% annually since 2002). Although improvement of the railway service quality implies a greater energy cost, it is the transportation mode that consumes less energy and that is one of the main arguments for public authorities to invest in railways (In Spain: 10,000 km of high speed lines are planned to be in operation in 2020). Since other transportation modes are improving energy efficiency railways should not neglect their competitive advantage and have to investigate and innovate to keep it.

Energy savings, quality, reliability, power peaks reduction, acceleration capacity when starting and voltage drops reduction at the catenary are some of the concepts considered in railway transportation research. These problems concern mainly DC railway lines DC (subways, short-distance trains and light trains). Energy Storage Systems is one of the main solutions to improve those topics and the one to be described in this paper. Recent studies from ADIF have concluded that in railway DC-lines the waste of energy due to regenerative braking is almost 20% of the consumed energy since the power can not be returned into the grid (due to diode rectifiers) and it could be re-utilized by means of energy storage devices. Moreover the number of diary supply interruptions could be reduced from 15 to 1 with the same technology.

The following decision is: What type of energy storage device is more appropriate for railways? There is not an easy answer and depends on the particular problem to be afford. Most of the publications and research works during the last years are focussed on on-board solutions for trains and present the solution of ultracapacitors or batteries. The on-board solution is more efficient since the energy storage device acts directly over the electric machine but a system off-board, connected to the DC catenary, has some other advantages such as no extra space occupied in the vehicle, no modifications in the train distribution and that the system can be connected to the catenary sector where problems are and not in every train. From the different off-board solutions Kinetic Energy Storage Systems (KESS) have been selected for this type of application. because of three main reasons: First, the high power and energy levels as well as energy/power ratio to achieve the requirements; second, the total cost is not so linearly increasing with the power and energy level compared to some other technologies like batteries or ultracapacitors; and finally the advantage of installing the system in a static location near the substation reduces the mechanical problems that flywheels or other technologies would introduce when mounting on board.

The Spanish Administrator for Railways Infrastructure (ADIF) in collaboration with the Institute for Energy, Environment and Technology Research (CIEMAT) and other 5 companies has promoted a project named FERRO_SA2VE (Advanced Energy Storage Systems. Applications to Railway Transportation), included in the frame of a bigger project SA2VE, to install some Kinetic Energy Storage System into a substation, stabilizing the electrical network around the railway consumption points by means of regulating the DC catenary voltage level and the power consumption.

The project results are being tested now at the laboratory at the same conditions (voltage level) that in the substation and will be moved shortly to it for testing with real train traffic.

The operation of the system consists on that the KESS is charged when a train is breaking, maintaining the energy and releasing it when another train is starting an a power consumption is detected, or even when a very low voltage level is detected at the DC catenary.

2. TECHNOLOGY DESCRIPTION

There are some commercial solutions of flywheels used for trains [Urenco, Piller, Pentadyne, Beacon, etc] and many technologies have been used in terms of type of machine, flywheel materials and power, energy and speed levels.
The system developed and presented in this paper is designed to be commercially competitive and presents several benefits: The technology is completely proper (machine, flywheel, power electronics and control); the materials used are conventional and the team has previous experience in fabrication of this type of electromagnetic devices, vacuum, power electronics and control platforms construction and testing, achieving an optimal cost and ensuring the success.

The system is composed by a metallic flywheel of 6 tons driven by a reversible switched reluctance machine used to increase and to decrease the speed and therefore the energy stored. Nominal speed is 6500 rpm and the total inertia of the flywheel is 895 kg·m². Figure 1 presents how the machine and the flywheel look like. Conventional ceramic bearings have been used but since the weight and speed level are too high for any commercial bearings, a magnetic levitation has been disposed by means of permanent magnets pulling up the metallic flywheel.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
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<tbody>
<tr>
<td>RPM</td>
<td>6600</td>
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<tr>
<td>Power</td>
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<tr>
<td>Energy</td>
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<td>DC Voltage</td>
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<td>4</td>
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<tr>
<td>Levitation</td>
<td>PM+Electrical</td>
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**Figure 1.** Electrical machine, the flywheel and system parameters.

The power electronics equipment is composed by the converter stage to drive the machine and the isolated DC/DC converter to connect to the railway DC catenary. Dedicated control hardware has been designed based on microprocessors and will be responsible of controlling the power electronics and communicating with the substation control.

**Figure 2.** Power electronics converters (machine-side, grid-side and catenary converter) and control platform.

**Figure 3.** Connection scheme at the laboratory but also at the substation.
Figure 3 shows how the KESS is connected to the DC catenary. At the Lab, the same voltage conditions are reproduced by means of a double secondary power transformer and a 12 pulses diode rectifier. A DC/DC converter is connected to the variable catenary voltage transforming the voltage level into the machine voltage range (750-900V) for the operation. An intermediate power transformer in an AC stage is used to the adaption, ensuring the voltage isolation from catenary. The machine-side converter (CLM) is used to drive the machine at the appropriate conditions depending on the load. Moreover there is a grid-side converter (CLR) to release the power into the AC grid when no catenary access is permitted in case of flywheel breaking necessity.

3. DESIGN CONSIDERATIONS AND EFFICIENCY

The main different of KESS with the other storage devices, and sometimes the reason to reject it, is the presence of mechanical problems. Due to the dimensions of this machine, the transversal inertial momentum is higher than the polar momentum, so as only cylindrical oscillation modes are possible. It is important to design the system to be subcritical, which means that the operation frequencies are lower than the natural frequency, in order to avoid mechanical resonances. Bearings temperature and accelerometers have to be tested continuously to detect this problem.

One of the main questions related to the convenience of kinetic energy storage technique is the efficiency. Several losses terms can be considered: iron losses, cupper losses and mechanical losses. Cupper losses are reduced by means of providing a very low current density wire for the machine coils (less than 2 A/mm$^2$ is recommended). Magnetization and demagnetization of the electrical machine produce some amount of iron losses, reduced by a bidirectional current operation. Nevertheless the most important losses are the air-friction losses of the flywheel that implies a reduction of the total system efficiency and complicates the cooling system.

Electric power has been measured following equation 1, considering the average power during a certain number of cycles, maintaining the flywheel spinning around the fixed speed of 5000 rpm.

$$P_{\text{losses}} = \frac{1}{m} \sum_{m=\text{cycles}} \left( \int_{t_{k-1}}^{t_{k+1}} (\epsilon - i) \, dt \right)$$

After several tests at 120 kW with different pressures (950, 500 and 250mbar), an average power consumption is presented in the figure 4b. Since the same power and speed is used, the intersection with the ordinates axis represents electrical power losses plus iron losses plus bearing losses. Figure 4.a presents a typical operation situation with some cycles to recover the rated speed and a discharge cycle. The number of charge-discharge cycles and also the frequency of these cycles is one of the important points to select this technology instead of others. The higher number of charge-discharge cycles the better efficiency is achieved for a realistic characteristic of machine fabrication and operation.

Pressure inside the machine is one of the key points in the design of this technology. The lower is the pressure inside the machine the higher efficiency is achieved. On the other hand by decreasing the pressure, lower fabrication tolerances are permitted, more expensive air-pump is needed and more isolation at the machine coils will be required (Paschen curve). Below 50mbar does not imply an important reduction of air friction losses. So as a pressure of 100mbar has considered as operation pressure. Figure 4.b. shows the extrapolation of power with the air friction losses.

![Figure 4. (a) KESS Operation. Speed and power during charging and discharging. (b) Friction loses with pressure.](image-url)
4. CONTROL OPTIMIZATION

The fast response of the energy storage system is one of the most critical requirements. In the case of the KESS, considering a SR machine, the response is really fast due to the low inductance (just a few microseconds to get rated power) but the problem is the power electronics behavior. Taking into account the DC links and the high time constants due to capacitances, it is important to provide an optimized control strategy to send information to every stage, compensating the time constants. CLM is in charge of receiving the system command to charge or discharge the KESS while the DC/DC converter is controlling the DC-link voltage. Giving information of the system command to the DC/DC converter and also providing appropriate P.I regulators parameters a better response can be achieve as figure 6 demonstrates. Strategy C is the optimal and a minimum oscillation in DC-link voltage is got during operation modes transition or reference changes.

Figure 5. Control scheme variables for the KESS connected to a DC catenary

Figure 6. DC-link voltage with different control strategies.

The control variable can be catenary voltage or current consumption from the substation. Voltage use to be very oscillatory and collateral substations can affect its value. Therefore, it was decided to consider the current at the substation to detect when the KESS has to be discharged and the catenary voltage as a reference for protection and to determine the moments of recharging the KESS.

5. EXPERIMENTAL RESULTS

Experimental tests connecting to the grid have been carried out before the tests connecting to the catenary. Figure 7 presents machine current waveform and network voltage and current in both motor and generator modes, and energy storage device response when a load demand is detected. 4 cycles are enough to get rated power and a 10% of DC voltage variation is produced.
Figure 3. Experimental results obtained when connected to the electric grid

REFERENCES


