

Development and Testing of a 200 MJ/350 kW Kinetic Energy Storage System for Railways Applications

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Abstract

In 2003, the Spanish Manager for Railways Infrastructure (ADIF) in collaboration with CIEMAT (formerly CEDEX, an Institute belonging to the Public Works Ministry of Spain), launched a project for developing a flywheel energy storage system for power management in railways substations with the aims braking energy recovery in conventional lines supplied with 3000 V DC.

At the time of presenting this paper, the first prototype of KESS (Kinetic Energy Storage System) is finished and has been tested at the CIEMAT facilities. Prior to these tests, two previous and smaller prototypes have been developed and tested in the same facilities.

The system is based on the use of a metallic flywheel, a switched reluctance motor/generator (SRM) and the corresponding power electronics, including a machine side converter and a grid side converter. 200 MJ (55.6kWh) of energy can be stored in a high strength steel flywheel, rotating over 6.000 rpm, which is magnetically levitated and guided with conventional high speed bearings. A power of 350kW can be exchanged in the electrical machine which is a switched reluctance, 6/4 poles, motor-generator, working in either single pulse or hysteresis band, depending on its speed. The machine is driven with a full H converter per phase, bidirectional in voltage and current thus reducing magnetic losses in the rotor of the SRM. Finally there is a grid side converter connecting the grid of the substation to a dc-link previous to the machine converter in order to supply single phase loads, controlled using a double hysteresis-band current strategy. A specific and very robust digital control platform has also been developed for this application to manage the complete system.

The paper will present also the tests of the KESS unit in a real electric substation specially conditioned by ADIF to perform these tests. This substation is very close to Madrid-Atocha station which is a really important railway junction of Madrid commuter lines. Tests in this substation will show the real functioning of the developed KESS as well as the level of reliability achieved in this pioneer project.

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. 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 (subways, commuter trains and light trains). Energy Storage Systems is one of the main solutions to improve those applications and will be described in this paper. Recent studies from ADIF have concluded that in railway DC-lines the waste of energy due to regenerative braking can vary between 8 and 25% depending of the kind of traffic. This energy can not be returned into the grid due to the substation 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 space distribution and that the system can be connected to the catenary , solving the catenary voltage problems considering whatever amount of trains.

Kinetic Energy Storage Systems (KESS) based on flywheels is appropriate for some applications when very high power, not high energy, large number of cycles and short period between charge and discharge operation. This technology has three main advantages: 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 or safety 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.

After testing the complete system in laboratory providing a catenary emulator, the system has been definitely installed in a DC railway substation and operated by interacting with real traffic.

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 $895 \text{ kg}\cdot\text{m}^2$ [13]. 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.

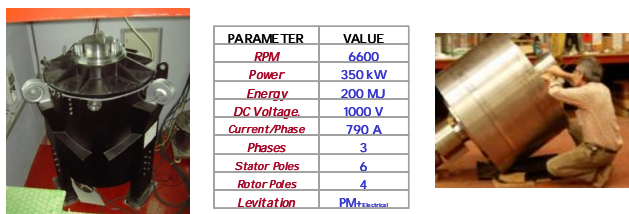


Figure 1. Electrical machine, the flywheel and system parameters.

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The power electronics equipment is composed by the converter stage to drive the machine and the isolated DC/DC catenary converter to connect to the railway DC catenary plus a three-phase inverter to connect the DC-link with the AC electric network. 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 at the laboratory tests.

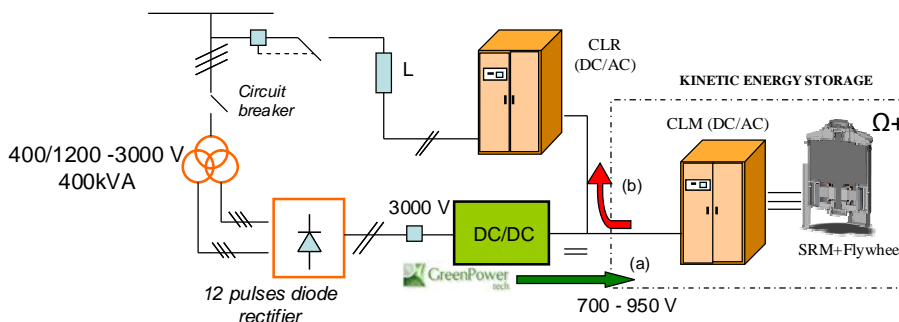


Figure 3. Connection scheme at the laboratory but also at the substation.

Figure 3 shows how the KESS is connected to the DC catenary during the laboratory tests. 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. Figure 4 presents the DC/DC converter topology. 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.

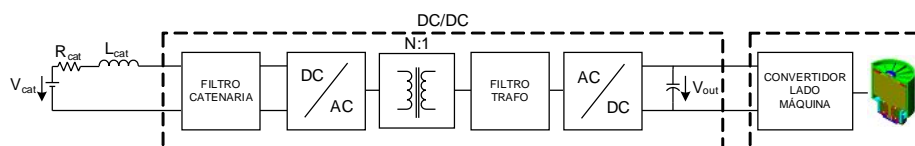


Figure 4. DC/DC catenary converter topology.

Figure 5 presents the connection at the railway substation, substituting the catenary emulator by the real catenary. The CLR converter is maintained to provide power to the AC network. The green line indicates the bidirectional power flux when train is requiring or supplying power from the catenary to the KESS. The red line indicates the power flux from catenary to AC network.

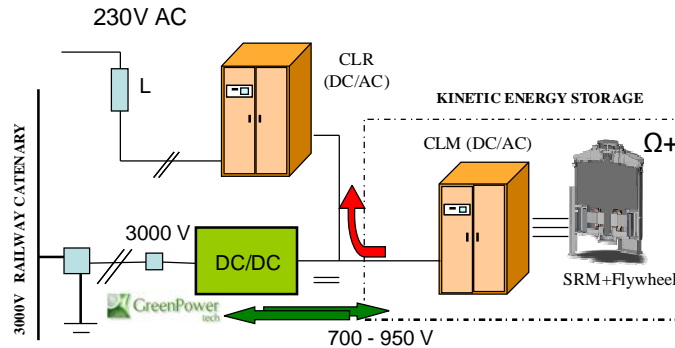


Figure 5. System connection at the railway substation.

3. INSTALLATION AT THE RAILWAY SUBSTATION

The system has been installed in a railway substation in Madrid ...



Figure 6. Machine and Flywheel installed in the substation, power electronics converters and control

4. OPERATION CRITERIA FOR THE KESS UNDER RAILWAY TRAFFIC

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, copper losses and mechanical losses. Copper 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.

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$$P_{losses} = \frac{1}{m} \cdot \sum_{m(\text{cycles})} \left(\frac{\int_{t_k}^{t_{k+1}} (u \cdot i) dt}{t_{k+1} - t_k} \right); \quad (\text{Equation 1})$$

After several tests at 120 kW with different pressures (950, 500 and 250mbar), an average power consumption is presented in the figure 7b. 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 7.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

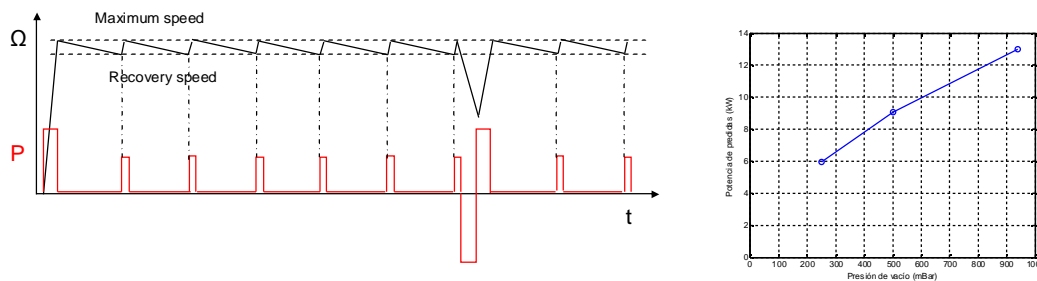


Figure 7. (a) KESS Operation. Speed and power during charging and discharging. (b) Friction losses with pressure.

The KESS has been proposed to work during the day, while is no exchanging any power during the night. During the day, it is named *operation mode*. The inner pressure is controlled around 150mbar and the machine can exchange power with the railway catenary. The efficiency depends on the amount of periods of power transmission and the periods when the speed has to be maintained (an average 6kW is required to maintain the speed around 3000rpm).

During night, it is named *storage mode*. It consists in reducing the pressure to 10mbar and maintaining during 8 hours the machine spinning without exchanging any power. During this time the speed is reduced 1500rpm without any additional losses and can be restarted the next day in operation mode again.

After testing the system under different scenarios of power and exchange frequency it has been observed that the most important limitation is the heating due to the system losses (mainly Joule effect losses in the electric machine and aerodynamic losses in the flywheel). The key elements more sensible to the heating are the machine coils and the bearings. Temperature has been measured in them determining a maximum value of 100°C for bearings and 120°C for coils. Under coils temperature limitation, and considering the heating and cooling response it has been concluded that maximum power to work continuously is 150kW. On the other hand under bearings temperature limitation, the system can spin at 3000rpm continuously. This way the energy able to be exchanged is 50MJ.

Figure 8 present the speed evolution during charge, discharge and maintenance operation.

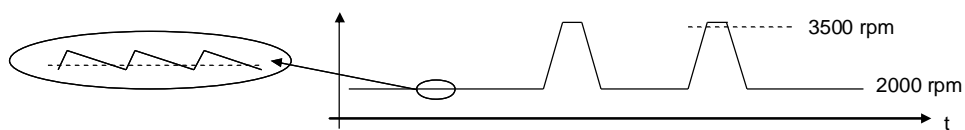


Figure 8. Speed pattern for the KESS during operation

5. EXPERIMENTAL RESULTS

Experimental tests connecting to the catenary have been carried out. Nevertheless, the operation under train demand has not been implemented yet. Several tests have to be passed without train interaction. Figure 9 presents machine current waveform in both motor and generator modes by simulating a train braking and acceleration.

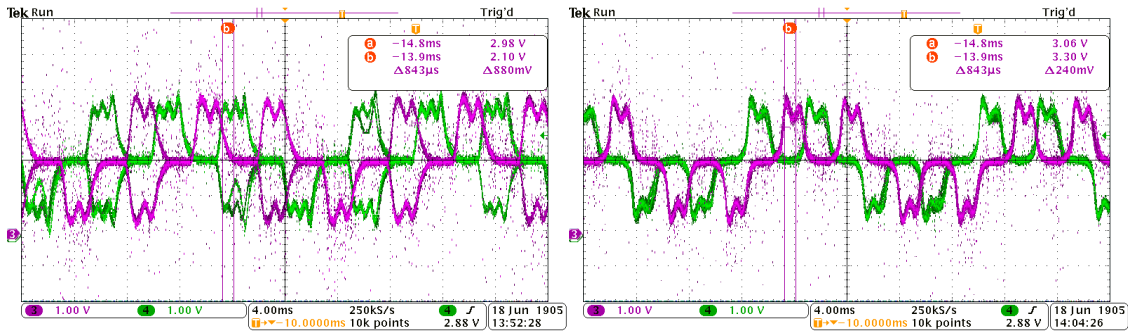


Figure 9. Machine current during motor (left) and generator (right) mode operation. 800A current and 3500rpm.

The system has been also provided with the possibility to supply power directly from the catenary to the AC-line. Figure 10 includes machine currents (only two of the three phase currents) while a certain AC load is supplied from the catenary (voltage and current maintaining the power factor). The control strategy decides when power exchange with the KESS and when with the AC.

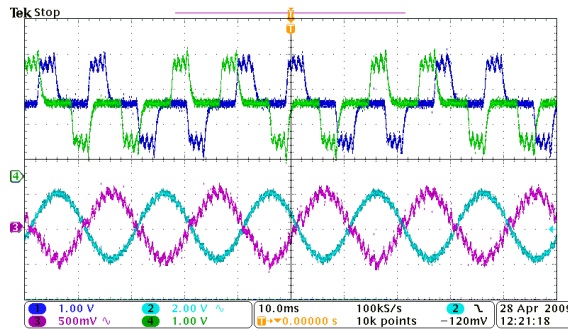


Figure 10. KESS supplying power to the AC network

Figure 11 presents and energy storage device response when a load demand is detected from the non supply mode. 4 cycles are enough to get rated power and a 10% of DC voltage variation is produced.

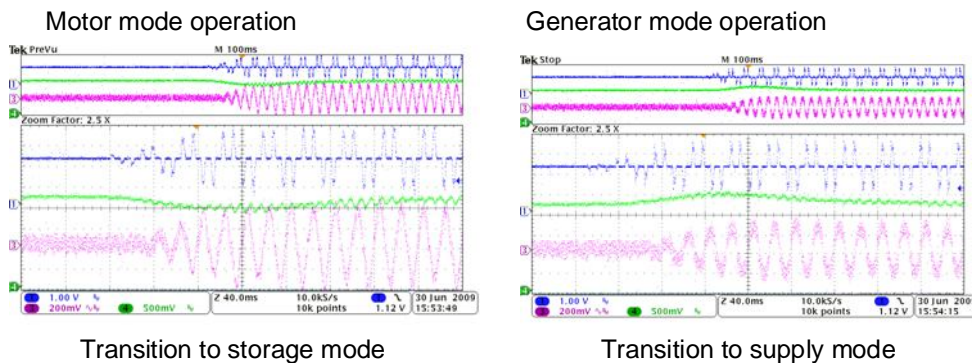


Figure 11. Transitions between KESS operation modes

6. MAIN CONCLUSIONS

This paper has presented the current situation of the project SA²VE jointly led by ADIF (Spanish Railways Infrastructure Manger) and CIEMAT (Institute for Energy, Environment and Technology Research) with the target of designing, developing and testing a Kinetic Energy Storage Unit (KESS) to be used for storing the braking energy of the trains and giving back this energy to the catenary. The main results obtained up to the date could be summarized in the following:

1. Although the system was initially conceived for been applied in high speed lines (HSL) to smooth the substation consumption and therefore reducing the nominal power of HSL substations, it was finally decided to be dedicated to storage braking energy in commuter lines where DC substations don't allow energy recovery to the network.
2. The system composed by the flywheel, high speed bearings, levitation system, electric switched reluctance machine, power converters (machine side converter, catenary connection converter and AC substation grid converter) and control system has been completely designed and built.
3. The whole system has been initially tested in the laboratory in several steps including various incremental power prototypes and although both the initial foreseen power and energy rates have been limited for technological reasons, the obtained results can be considered satisfactory.
4. The system, after setting up an ADIF substation in Madrid commuter lines, is already installed there and connected to 3000DC V catenary. First tests have been already performed but, as the final target of these tests are to check the robustness and reliability; final results will be evaluated after testing the installation during the whole year 2011.
5. Finally, the application of this Energy Storages system to DC lines can save an important amount of energy which is currently dissipated in the braking resistors. According to ADIF's analysis this energy can fluctuate between 8 and 25% of the total consumption, and ADIF is working not only in this direction but also in developing reversible substations which can, together with KESS, contribute to improve the Energy efficiency of the Railways system.

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