The ACE^2 System: A Kinetic Energy Storage for Railway Substations

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1. - Introduction

In the year 2002, the Spanish Administrator for Railway Infrastructure (ADIF) launched a project, partially supported by the Spanish Ministry of Science and Education to develop a Kinetic Energy Storage System (KESS) to level the power consumption of Substations of the High Speed Train Lines. One of the main reasons to include the KESS is to stabilize the electrical network around the railways electrical consumption points. The first full prototype of the system has been completed now and it is under commissioning. A second prototype will be finished within the next few months and after initial trials, it will be installed in a Substation, where it will be tested under operational conditions.
Besides ADIF, the project has been developed in collaboration with two official R&D Institutes and private companies. A second stage within the project has begun in order to improve the performances of the system as well as to extend the number of applications [1], such as urban trains, uninterruptible power supplies or energy management in ecological buildings.

2. - Overall Description of the System

Although different Energy Storage systems are in common used for industrial and transport applications, Kinetic Energy Storage System (KESS) was selected. It has been considered a better option than superacapacitors for these particular high power and energy densities, resulting a much lower cost. The main disadvantage of this system is the mechanical complexity introduced by the flywheel, bearings, magnetic levitation, etc. Nevertheless, previous experience and good results in previous projects is the key point of its success.
The current KESS [2][3] is based on the use of a high strength steel flywheel rotating up to approximately 7.000 rpm, an electrical machine acting both as a motor to store energy and as a generator to release the energy into the network. A double power electronics converter composed of a machine-side converter (MSC) to drive the machine and a grid-side converter (GSC) to pump the energy to and from the ac mains. A modular control system is being in charge of establishing the net flow of power between the grid and the energy accumulator. This flow acts on the power electronics converter based on the power reference values.
The overall amount of stored energy is 200MJ (55,5 kWh) and the maximum continuous interchanged power is 350 kW. Although the net interchanged energy is 100 MJ (from the maximum capacity down to half the capacity of the KESS) the peak values of power can rise up to 500 kW. Several units will be located at the railway substation as Figure 1 shows.

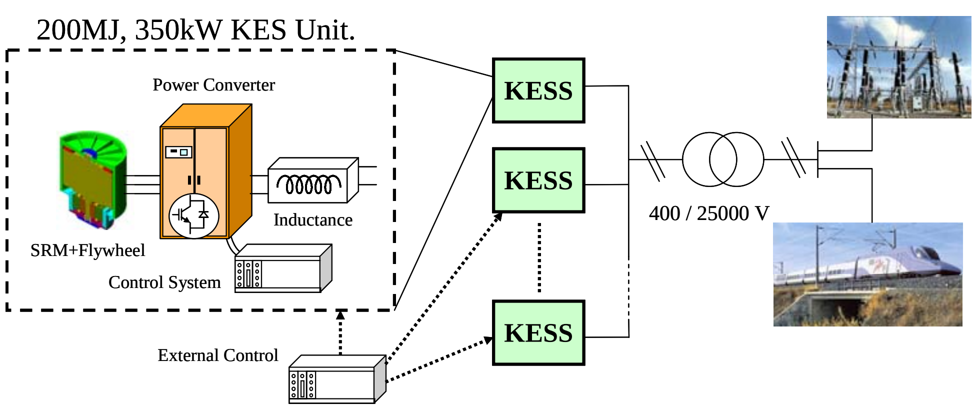
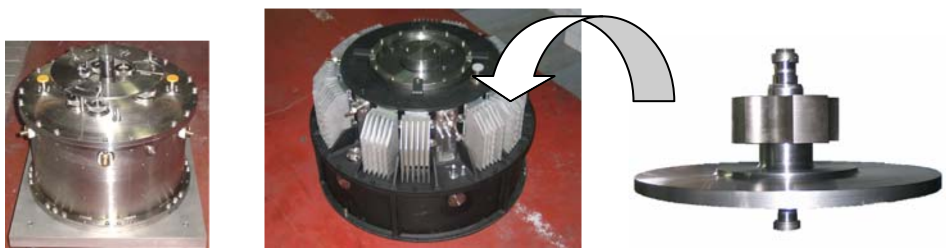


Figure 1. Complete KESS distribution scheme for railway applications.

3. - The Flywheel, Levitation System and the Electrical Machine

The part of the system where the energy is physically stored is the flywheel which is made of a high strength steel alloy, forged and machined to an almost-cylindrical shape avoiding stress concentration at any point and reducing them to the maximum theoretical value which is located in the axis of the cylinder. The shaft of the flywheel is machined from the same initial piece. Its lower part holds the rotor of the electrical machine and the bearings are placed at each end of this shaft. The overall weight of the flywheel is 6 Tons and in order to reduce the load of the bearings, it is magnetically levitated using a hybrid system of permanent magnets and one electromagnet which adjusts the net weight to the required optimum value. Guidance of the flywheel is achieved by conventional high speed ceramic bearings. The rotating mass is working in a vacuum in order to reduce frictional losses.
To rotate the flywheel a 6/4 Switched Reluctance Machine is used [4]. Although other electric machines suit the KESS application, for example PM synchronous and induction machines, a switched reluctance machine was selected mainly because of its low cost, robustness and low rotor losses.
Its rotor is shrank fitted in the shaft of the flywheel and its stator in the housing of the system. The machine has been designed taking into consideration not only electromagnetic parameters to achieve the required power, but also mechanical aspects to guarantee a level of stresses in the rotor compatible with those of the flywheel.
Prior to the fabrication of the final prototype, two small prototypes were built: One with only the SRM machine (Figure 2.a.) and a second with the machine and a small flywheel (5 MJ) to test the main concepts, including the bearing mounting and rotor position detection (Figure 2.b.).



(a) **(b)**

Figure 2. Switched reluctance machine prototypes previous to the final prototype.

The final prototype is provided with a higher power machine (350 kW) and the larger flywheel (200 MJ). A low pressure atmosphere inside of the machine considerably reduces the aerodynamic losses of the flywheel. On the other hand, more complex machine design is required to guarantee a pressure isolation. Extra isolation being required at the windings and the feedthroughs. Breakdown voltage is reduced with the pressure as the Paschen's law [5] demonstrates.

V = f(p,d) , where 'p' is the pressure and 'd' is the distance.

The theoretical relationship for the direct current breakdown voltage of two parallel-plane electrodes immersed in a gas, as a function of the gas pressure and electrode separation, is shown by the Paschen curve. This relationship predicts the occurrence of a minimum breakdown voltage for a certain product of the pressure times the separation. Therefore the electric isolation required is higher as the pressure is reduced inside the machine.
As for the bearings, since no commercial bearings are available to simultaneously support the speed and axial load, a magnetic levitation system has been provided to reduce the axial load, leaving only 500 Kg so as to ensure the mechanical stability of the system. Two levitation systems based on permanent magnets and electric coil are in charge of reducing the load on the bearings.

4. - The Power Converters

A double electronic converter is used to drive the KESS, composed of a MSC and a GSC sharing a common DC link. The MSC is in charge of driving the switched reluctance machine [6][7][8][9][10] and the GSC is in charge of controlling the DC link voltage and connecting the system to the network.
Figure 3 shows the power electronic circuit topology used to drive the machine.

The DC link voltage varies from 650 V to 1000 V depending on the machine speed in order to achieve the single pulse situation at the machine phases and reducing the commutation losses. Average commutation frequency at the MSC is 600 Hz. Full-bridge IGBTs topology has been chosen for the MSC to get bidirectional current, maintaining the magnetic orientation at the rotor and minimizing the rotor losses [11]. Moreover, soft-switching techniques and a balanced commutation between the IGBTs have been implemented to maintain the same stress level in all the switches.

Since only single-phase connection is permitted at the railway substation, GSC topology also acts as a full-bridge and it is operated by a double-hysteresis band current control strategy. Charging and discharging energy cycles is important for the thermal design of the power electronics devices. Output voltage is 400 V because the electric isolation requirements at the machine, which is increased to 25 kV at the substation by means of a power transformer.

Figure 3 shows the power electronics converters topology as used to drive the KESS.

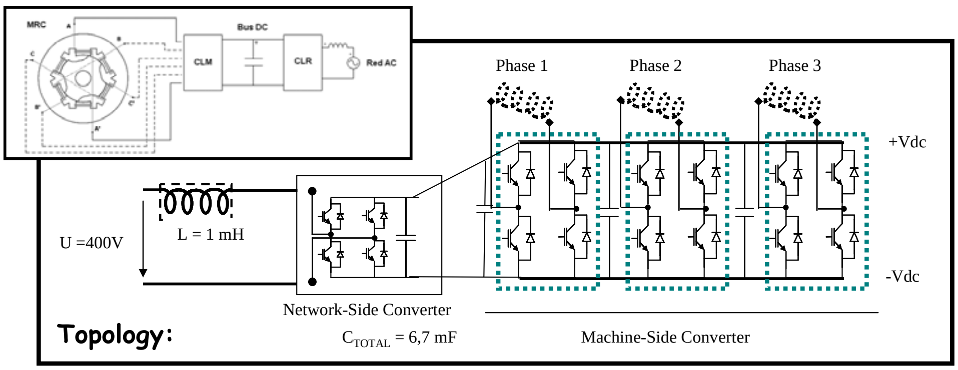
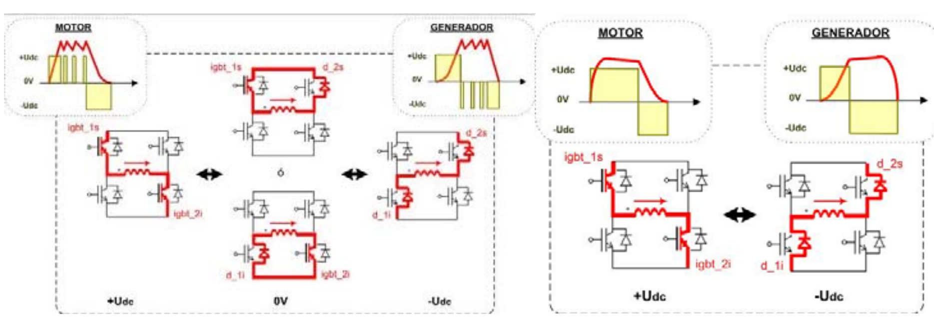


Figure 3. Power Electronics Converters topology used to drive a KESS connected to a single-phase grid.

From 0 to 4500 rpm the machine is supplied with 650 V and the current level, due to the reduced electromagnetic force, is controlled by hysteresis band strategy. Equation 1 presents the current evolution in a saturated machine. The usual operation range is between 4500 and 6600 rpm whilst the DC voltage is controlled so as to achieve a single pulse current in the machine phases. As a result, the commutation losses at the converter and the hysteresis losses in the machine are being reduced to their maximum.

$$\frac{di}{dt} = \frac{V_{dc} - R \cdot i - w \cdot \dfrac{d\lambda}{d\theta}}{\dfrac{d\lambda}{dt}} \qquad \text{(Eq.1)}$$

Figure 4 shows the different commutation modes for the MSC, hysteresis-band and single-pulse. Current and voltage are shown in the schemes with IGBTs status so as to share the electrical stress. During hysteresis band operation, +Vdc, -Vdc and 0 volts are applied to the machine phases to control the current. During single-pulse operation, just +Vdc and –Vdc is sufficient to control the current whilst the commutation frequency is reduced to the value of *w(rpm)/30*.



(a) hysteresis-band mode *(b) single-pulse mode*

Figure 4. Machine-side converter commutation modes and experimental results.

Figure 5 presents some experimental results obtained when the KESS was charged and discharged in different operation modes. Machine current and network voltage and current are displayed. Bidirectional machine current can be identified at the illustration.

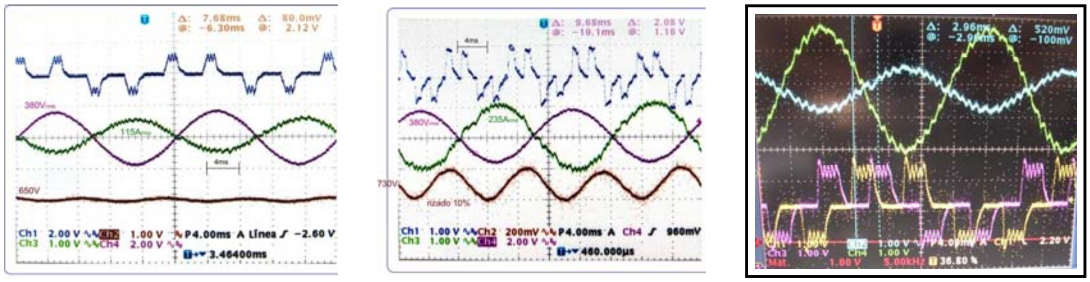


Figure 5.a. SRM charging operation (motor mode) at different speeds.

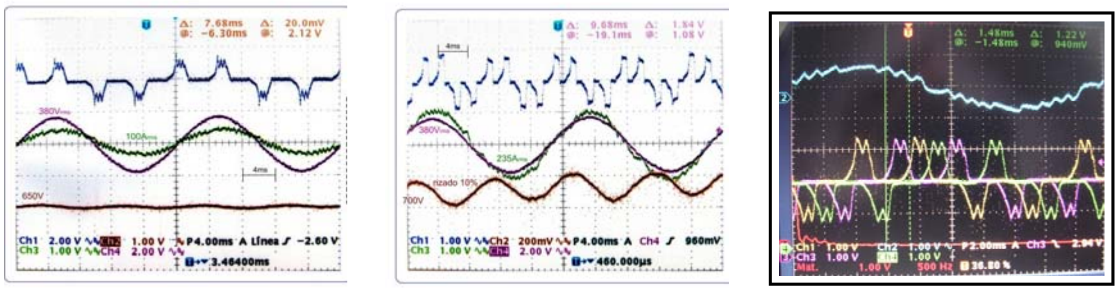


Figure 5.b. SRM discharging operation (generator mode) at different speeds.

5. - The Control System

Full-bridge converters provide each stator winding with independent driving circuits. The proposed control architecture reproduces this idea to achieve a totally independent operation (electric and electronic) for each bridge. In this way, a decentralised control architecture based on microcontroller boards connected through a 1Mbps CAN network is used. The on-board basic circuit is a 16-bit single-chip Renesas H8s2623 microcontroller working at clock frequency of 20 MHz. Modularity and decentralisation allows to distribute tasks in order to achieve very short cycle times, which are needed to deal with the high *di/dt* managed at the machine-side (f_{sample}>50kHz). The flexibility of this design makes it suitable for prototype systems, as it is easily adaptable to different machine topologies and/or changes in the control strategies. Besides, this scheme allows the controller to grow larger in a loose manner, adding additional boards for controlling or monitoring other possible subsystems. Figure 6 shows the control modules scheme for one KESS unit and the control required for a complete Energy Storage Plant.

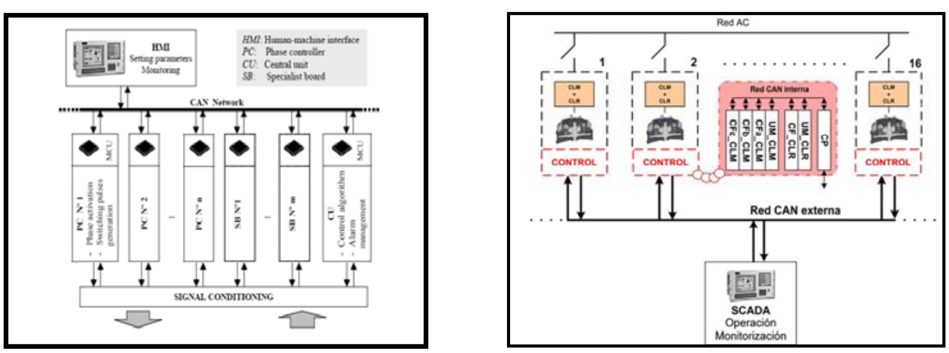


Figure 6. KESS control scheme based on a distributed architecture. Control scheme for a complete ES Plant.

The SRM operation requires a very precise position detection. The control system receives three position signals from the SRM originating from three laser sensors, in order to determine the machine phase activation sequence and the speed estimation as presented in Figure 6. A sensorless strategy is being developed obtaining the position and speed though the current measurements. It will substitute the laser sensors, thus reducing the total cost.

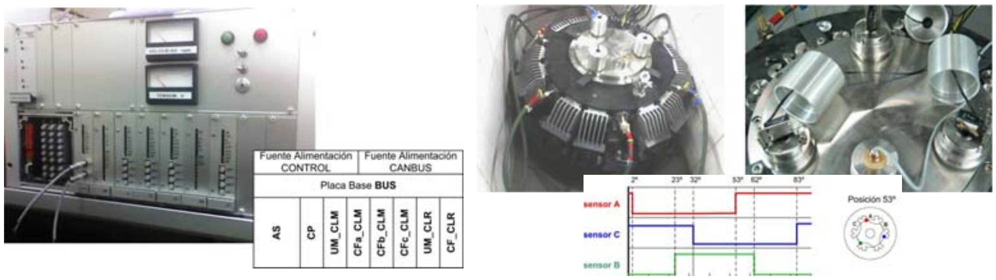


Figure 7. Control boards and laser sensors to estimate position and speed.

The current and voltage measurements received by the control boards are firstly filtered to avoid electromagnetic noise. The control boards and rack are designed so as to achieve a good EMI protection. Moreover, the control desk is located 20 m from the power converters and machine and the IGBT's switching signals are sent though optic fibre.

6. – Laboratory Testing Facilities

CEDEX has invested in some testing facilities for Kinetic Energy Storage Systems in order to acquire the appropriate mounting and transportation tools, power supply levels and safety measures.
The final prototype has been tested for the application of energy storage in railway systems but not with the maximum power. It is planned to test it at rated power in a few weeks.
On the other hand, some transportation companies related to railway applications like subway and intercity trains are interested in Energy Storage Systems and a new project has been launched to continue developing these technologies.
Figure 8 shows the Energy Storage Laboratory in CEDEX. The KEES prototypes are located inside of the pit. Power electronics converters are also presented at the picture.

Figure 8. Energy Storage Laboratory in CEDEX.

7. - Conclusions

A complete Kinetic Energy Storage System has been developed to smooth the power consumption profile in a railways substation, always very irregular due to trains coincidence, starting, braking, etc. The system has been designed to be robust, and maintenance free, using well-known technologies which have been pushed to reasonable limits. The development has been confirmed with the fabrication and tests of intermediate prototypes and it is now starting the first running tests at a pilot facility. A second prototype will soon be concluded and taken to a substation for real tests under traffic conditions. A sensorless strategy will substitute the laser sensors to estimate the rotor position and speed.

Finally a second generation of KESS is under development in the framework of a new R&D program which includes magnetic bearings, advanced control and new applications for these systems.

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