# Use of Flywheels in High Cycling Applications

Octavio Solis (VYCON, Inc., Cerritos, California, U.S.A); osolis@vyconenergy.com
Louis Romo and Patrick McMullen (VYCON)

Flywheel energy storage systems (FESS) have been accepted in a variety of UPS applications, such as ride-through power for backup generators in mission critical redundant back up power systems. Recent flywheel technology advancements, including magnetic bearings, new magnet materials, composite materials, and integrated power conversion and controls, have allowed flywheel technology to advance in performance and broaden acceptance in a larger range of markets. These advancements are allowing for FESS technology to gain traction and market acceptance in several new markets where flywheel systems can significantly improve system performance and reliability.

A large market for energy storage systems exists in applications such as electric transit power savings, electric transit voltage regulation, shipyard cranes, elevators, mines, and wind power generation. For each of these applications, the power support requirements are in the time frame of less than 30 seconds. The introduction of an effective energy storage system into these applications can provide significant, quantifiable improvements. The keys to addressing these applications, where more conventional energy storage technologies fall short, are in meeting the cycle frequency and system life with minimal maintenance to provide an adequate return on investment (ROI).

Customers in these markets recognize the impact of and costs associated with short duration peak power demand, and are actively investigating possible solutions with available technologies. This paper takes the example of a typical light and heavy rail power demand and evaluates the strengths and weaknesses of the candidate technologies against the requirements necessary to be a cost effective solution. To do this, the evaluation not only includes performance, integration, and operating life, but also the life cycle cost of each system to arrive at the effective ROI of each energy storage approach. A conclusion can then be drawn as to which energy storage approach best suits the needs of the transit requirements and what ROI can be realized with the selected approach.

## Typical Requirements for a Transit Energy Storage System

In order to be an effective transit wayside energy storage system (ESS), the ESS must be able to capture and enable reuse of train braking energy which would otherwise be lost. For major urban rail lines, the ESS must operate at a high duty cycle during long rush hours with close headways. For example, the ESS must operate at a duty cycle above 40% (i.e., 15 second discharge, 20 seconds of idling, 15 seconds of charging, and 20 seconds of idling and repeat the cycle) for a 4 hour period.

The ideal ESS should be automatic, safe, maintenance-free, self-protecting during emergency or failure conditions, and highly efficient with very low waste energy during discharging, charging, and idling. Additionally, the ESS must be stable under all conditions and electromagnetically compatible with the signal system and other equipment. The ESS must permit low-cost installation and be modular for installation in existing available floorspace with minimal heating/cooling requirements. Finally, the ESS must be easily connected to the traction power system.

## Technologies

The technologies available to support the high cycle applications include supercapacitors, batteries and flywheel systems. Table 1 illustrates a comparative summary of these technologies:

Table 1. Technology Comparison Summary.

| **Technology Comparison** | | | |
|---|---|---|---|
| **Feature** | **Flywheel** | **Supercapacitor** | **Battery** |
| Energy density | ⊙ | ⊙ | ● |
| Cost / kWh | ⊙ | ⊙ | ● |
| Power density | ● | ● | ○ |
| Cost / kW | ● | ● | ○ |
| Maintenance needed | ● | ⊙ | ○ |
| Configurable rating | ● | ● | ● |
| Operating life | ● | ○ | ○ |
| Proven technology | ⊙ | ⊙ | ● |
| Hazardous materials | ● | ○ | ○ |
| Now in service | ⊙ | ● | ⊙ |
| Key: ● Better ⊙ Average ○ Worse | | | |

Battery energy storage systems (BESS's) have enormous energy capacity with low unit cost per kWh compared to flywheels or supercapacitors, but have a high cost per kW. The BESS challenge is to provide a high enough power rating without an unnecessarily large and expensive energy capacity. To date, the BESS has not been able to meet this challenge. Batteries also posses low cell voltage, requiring many cells in series to achieve the high voltage required in the target applications. This results in higher system cost, increased overall volume, and issues with maintenance and reliability. Since BESS store energy chemically and are strongly dependent on operating temperature, batteries have a short life and require high maintenance when compared to flywheels and supercapacitors. As a result, for high cycle applications, the life cycle cost of BESS is high and not an economical solution. Additionally, battery electrolytes are usually toxic and corrosive, and cannot provide deep, continuous charge/discharge cycles without impacting battery life.

The supercapacitor energy storage system (SESS) has no moving parts, requires little maintenance, and appears suited for both railcar and wayside applications. The SESS cost per kW is lower than batteries yet higher than flywheels, and has a higher cost per kWh than either a BESS or a FESS. Supercapacitors also posses very low cell voltage, requiring many cells in series to achieve the high voltage required in the target applications. The SESS can be designed for deep, continuous charge/discharge cycles, but its capacitor life strongly depends on voltage stress. Long operating life can be achieved by reducing the change in capacitor voltage during discharge, requiring many capacitors in series to achieve the necessary operating voltage. This configuration results in increased cost, volume, and presents issues in maintenance and reliability. Additionally, the SESS contains dielectric fluids which are typically both toxic and flammable.

Modern flywheel energy storage system (FESS) technologies use steel or composite rotors, high performance insulated gate bipolar transistors (IGBT's), digital signal processor controllers, magnetic bearings, and high power density motor/generators. A key FESS advantage is the ability to provide deep charge/discharge cycles without wear or degradation. A FESS has a low cost per kW and a higher cost per kWh when compared to batteries, but lower than supercapacitors. An operating life of 20 years is practical for a rail application with a FESS that can be highly reliable requiring little maintenance, especially if equipped with fully active magnetic bearings. A FESS equipped with a steel flywheel mass is less affected by extreme temperatures than other energy storage technologies, including composite rotor FESS. In order for a FESS to operate on a railcar, the FESS must be able to accommodate the gyroscopic reaction force when the FESS is spinning about its axis, requiring special mounting. The FESS design must resolve safety concerns associated with energy containment since the FESS is a mechanical device.

The FESS capabilities of supporting high cycle requirements, as in the electric transit application, are based on two key technical areas:

- Temperature control
- Maximum number of cycles of the system

Temperature Control
A FESS with a permanent magnet rotor assembly has the capability to achieve high cycles based on the low losses of the rotor assembly. This configuration creates heat at the stator assembly section allowing for heat transfer through the external housing to the outside ambient. Additional means of cooling are easily achievable with this configuration if required.

Maximum number of cycles of the system
Advances in magnetic bearing technology have provided FESS with extended life by replacing traditional ball bearings or bearings with complex oil lubricating systems. The hub materials used in new FESS can also provide long life with a high number of cycles. The primary types of materials used to store the kinetic energy are composite materials and high strength steel materials. Recent advancements in non destructive evaluation testing, metallurgical, and material processing has allowed for both composite and steel flywheels to be viable and safe solutions for high cycle applications.

A number of flywheel companies have installed demonstration projects in the transit industry. Some examples include New York City Transit, London Underground, Paris, and Lyon, France. The highest rated unit demonstrated to date is a 1 MW, 7kWh FESS, and larger units are now under development.

**Energy Saving Objectives**
Using an electric rail transit example to analyze the effective benefits of an ESS, the ESS must be able to provide the following two key energy saving objectives:

1] Reduction in Total Energy Consumption: The ESS must capture and enable reuse of energy regenerated by braking trains, thereby directly reducing the Transit Operator's energy costs.

2] Reduction in Peak Power Demand Charges: The ESS must reduce peak power demand charges as electric utilities charge industrial customers for peak power demand, in addition to charges for total energy used. Peak power demand is determined by the time period(s) with the highest energy usage. Reducing the energy used during these peak demand periods can deliver significant cost savings. Figure 1 illustrates a typical installation of a wayside ESS.

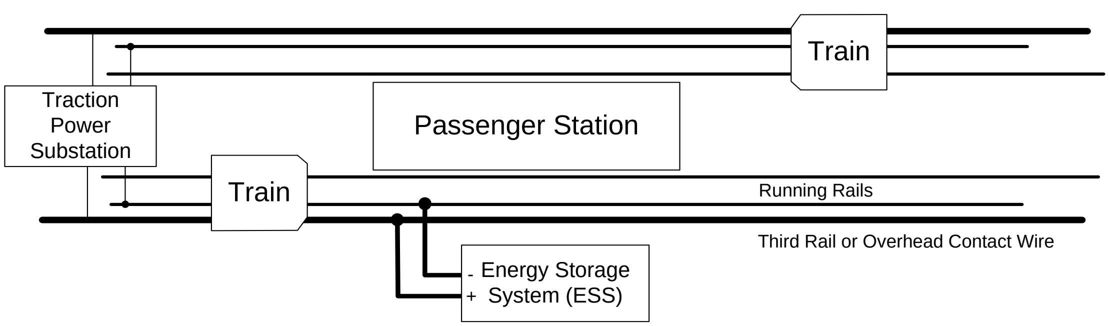


Figure 1. Typical Wayside ESS.

**Energy Savings Case Study**
A Traction Power Cost Analysis (TPCA) tool was developed to evaluate the ESS savings. The TPCA models the power flow between the traction power supply, the train, and the ESS. Inputs include the train acceleration and braking current and voltage profiles versus time, as well as operating characteristics for the rail line including schedule, train length, and headway.

The ESS power rating is an adjustable parameter which is used to select and optimize the ESS configuration. To simplify calculations, the TPCA uses train regenerated energy as an input, and constrains the energy returned by the ESS to balance the input quantity. The TPCA calculates the energy used by the train and saved by the ESS, per car per stop/start cycle. The TPCA extends the calculation to cover the rush hour, day, and year. It also calculates the average power used in the peak power demand interval. Finally, it calculates the resulting costs and savings.

A dense East Coast heavy rail line with ten car trains and a West Coast suburban light rail line were analyzed with the energy and peak power demand costs illustrated in Table 2.

Table 2. Energy and Power Costs

| | East Coast | West Coast |
|---|---|---|
| Energy Cost | $0.07 / kWh | Variable by time of day and season:<br>~$0.08 / kWh base<br>~$0.13 / kWh during summer peaks |
| Peak Power Demand Cost | ~$7.0 / kW monthly charge, set by the maximum half hour of peak demand in the month | Variable by time of day and season*:<br>~$0.34 / kW monthly charge for the max half hour<br>Plus ~$0.70 / kW monthly charge during Partial Peak hour<br>Plus ~$7.5 / kW monthly charge during summer Peak hour. |
| * - Definitions of Peak and Partial Peak hours depend on the season. In a typical summer work day, Peak hours are 12 noon to 6 pm, and Partial Peak hours are 8:30 am to 9:30 pm. | | |

Additional TPCA inputs are illustrated in Table 3. All traction power savings result from the capture and reuse of train regenerated energy. The peak power demand is too long for the reduction of instantaneous power to translate directly into a reduced peak power demand charge. Therefore, two sets of real-world parameters govern ESS effectiveness in energy and peak power demand savings. Included are the power and energy characteristics of train regenerative braking and the ESS power and energy ratings compared to the train's characteristics. Figures 2 and 3 show power and energy profiles vs. time for the train, ESS, and substation, for the US heavy rail and light rail line. The train power profile versus time is from typical field measurement data. The substation curve shows the traction power supply output, which is the difference between the train usage and the ESS supply. The energy curves are the corresponding time integrals of the power curves.

Table 3. Additional TPCA inputs.

| | US East Coast (Heavy Rail) | US West Coast (Light Rail) |
|---|---|---|
| Train length | 10 | 2 to 4 |
| Operating hours per day | 24 | 20 |
| Rush hour headway | 2 min. | 15 min. |
| Train load assumption | AW2<br>* - Fully Loaded, passengers seated only | AW2 |
| Flywheel rating | 2.0 MW | 0.6 MW |
| Peak power demand period | 15 min. | 5 min. |

Table 4 summarizes the results and effective energy savings and peak power demand reduction. For the modeled heavy rail line with ten-car trains at a seated passenger load, a properly sized ESS of 2.5 MW rating will provide energy savings of up to 6.4 kWh per train start/run/stop cycle, for an energy savings of 31 % compared to a cycle with no regeneration. This equates to a savings of 5.4 MWH per day per ESS. Using the Table 2 energy costs, this is a savings of $113,000 per ESS installation per year.

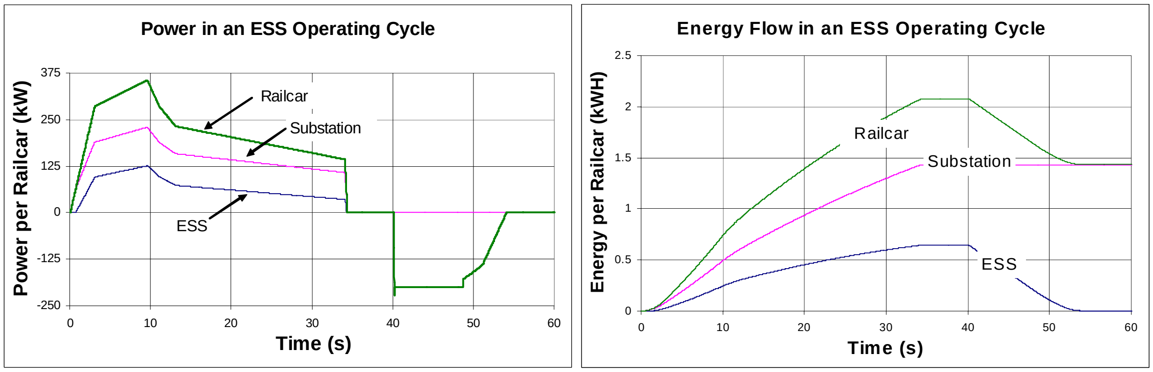


Figure 2. US Heavy Rail Power and Energy Flow Curves in an ESS Operating Cycle per Railcar.

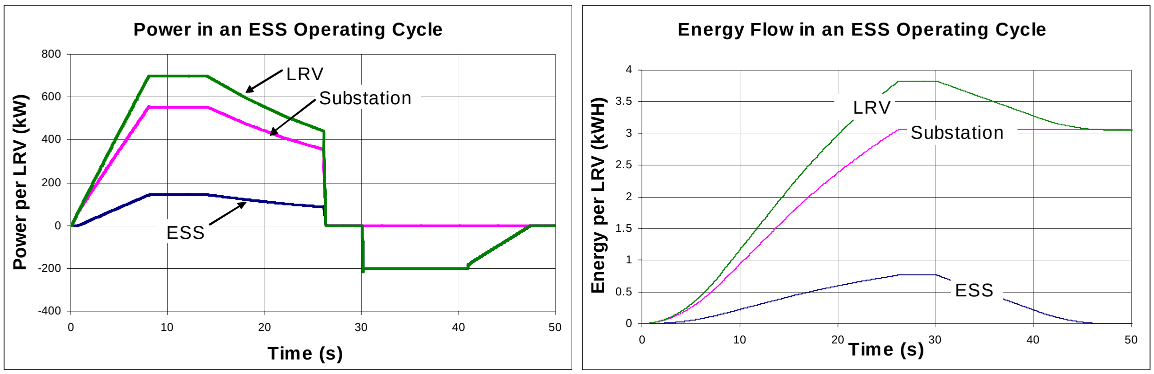


Figure 3. US Light Rail Power and Energy Curves in an ESS Operating Cycle per Railcar.

Table 4. ESS Results Summary.

| | US East Coast (Heavy Rail) | US West Coast (Light Rail) |
|---|---|---|
| Projected Energy per cycle w/o ESS | 21 kWh<br>(10 car train) | 9.6 kWh<br>(2.5 car avg. train) |
| Energy recovered per cycle | 6.4 kWh<br>(10 car train) | 2.2 kWh<br>(2.5 car avg. train) |
| Energy recovered per cycle, % | 31% | 23% |
| Energy recovered per ESS per day | 5.4 MWH | 0.23 MWH |
| Energy Saving per year | $113,000 | $7,600 |
| Peak Power Demand w/o ESS | 1,200 kW | 830 kW |
| Peak Power Demand Reduction, kW | 193 kW | 100 kW |
| Peak Power Demand Reduction, % | 16% | 12% |
| Power Savings per year | $32,000 | $5,900 |
| Total Savings per year | $145,000 | $13,500 |

The ESS will reduce the peak power demand averaged over a fifteen minute interval for 10-car trains on two tracks, from 1,200 kW to 1,007 kW per train for a per-train savings of 193 kW. This 16% peak power demand reduction yields a savings of $32,000 per year. Thus the total potential savings per year per ESS is $145,000 minus maintenance costs.

The modeled light rail line has a smaller power demand and therefore would require a smaller ESS. It has trains of two to four cars depending on time of day, with a day-long average train length of 2.5 cars. With a seated passenger load (AW2), a 0.6 MW ESS will provide energy savings of up to 2.2 kWh or 23% per train start/run/stop cycle. This yields a savings of 0.23 MWH per day per ESS. This is a savings of $7,600 per ESS installation. ESS peak power demand reduction, averaged over a five minute interval for four-car trains on two tracks, is 100 kW, reduced from 830 kW to 730 kW or 12% of the total peak power demand.

The return on investment (ROI) for both the US heavy rail and light rail line is presented in Figure 4 as a function of ESS capital cost per MW. For a FESS priced between $125,000 and $150,000 per 500 kW ($250,000 to $300,000 per MW), a ROI ranging between 20 to 25% can be expected in a heavy rail line. Recently published information from a supercapacitor manufacturer for an equivalent SESS solution would result in a price of approximately $380,000 per MW resulting in a ROI of about 15%.

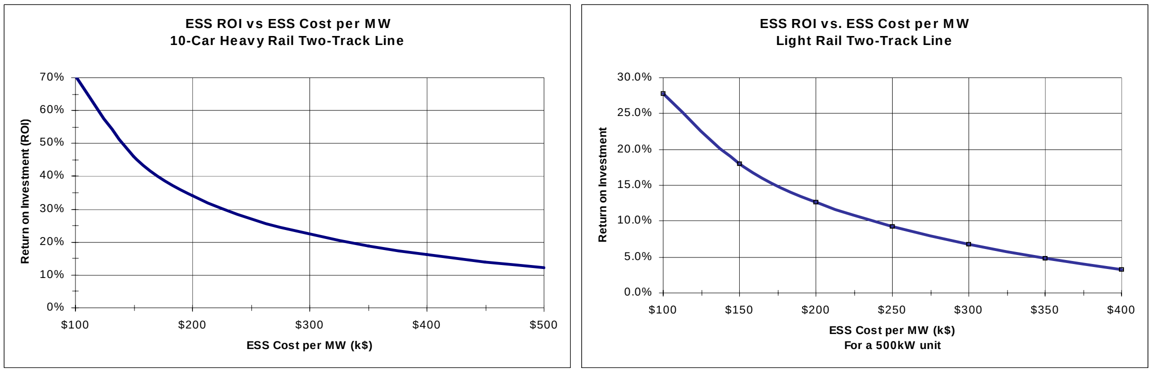


Figure 4. ROI versus ESS cost for US Heavy Rail and Light Rail.

**Conclusions**

In the example of a transit system, there is a clear advantage in the installation of an ESS for power and energy recapture. The ability of an effective ESS is not only being capable of capturing the regenerative energy from the train braking system, but it must also be able to cycle up to every 2 minutes for several hours and provide a system life of at least 10 years. Based on the high demand of this application, a flywheel ESS designed with a permanent magnet motor/generator and active magnetic bearings is the best solution. Additional applications, similar to the electric transit application, include wind power load leveling, peak power shaving and fuel savings in cranes and elevator peak power savings among others.

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