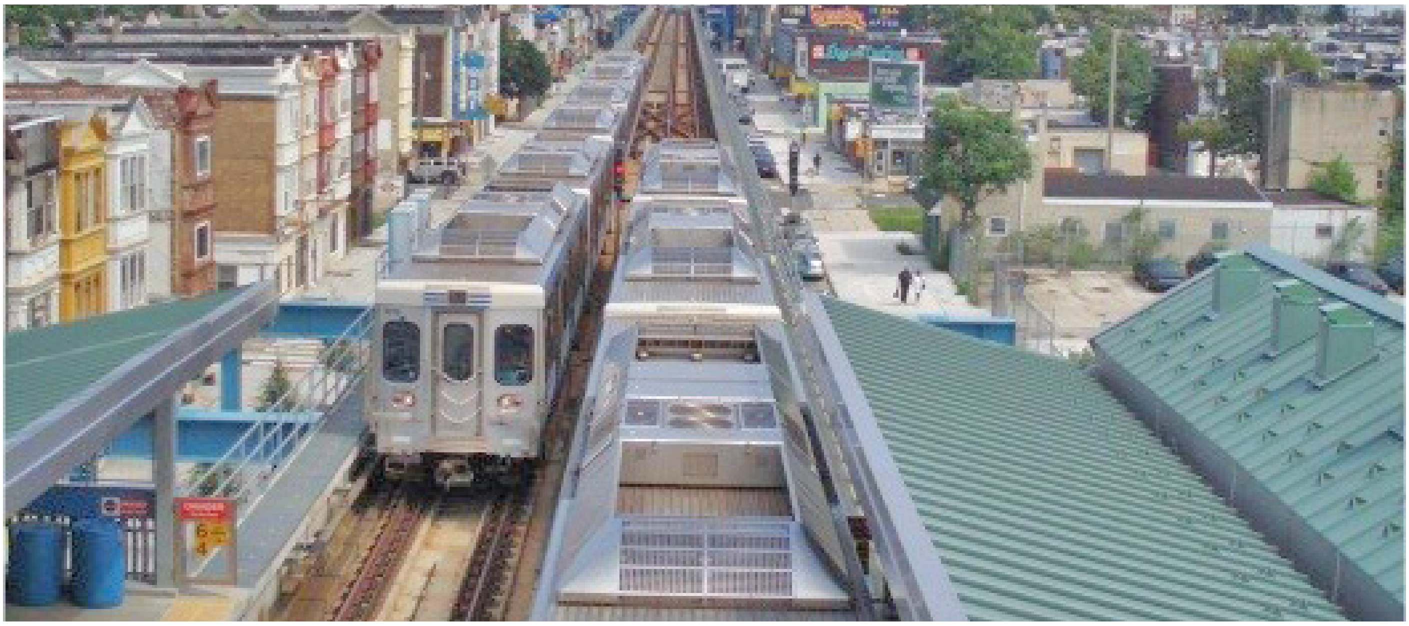
White paper

SEPTA's (Southeastern Pennsylvania Transit Authority) Wayside Energy Storage Project



SEPTA's Market Frankford Line

Project background and objectives

SEPTA's wayside energy storage initiative has received national and international recognition for its innovative integration of rail energy efficiency and smart grid technologies into an aging transit infrastructure. This project has the potential to transform the relationship between the transportation and energy industries.

SEPTA is the second-largest consumer of electricity in its local energy company's service territory. Facing increases in energy costs, SEPTA needed to find creative ways to become both environmentally and economically more efficient. Given that more than 80 percent of the nearly 500,000,000 kWh of electricity used by SEPTA is for propulsion power, recovering energy lost during braking is one of the most potent of SEPTA's sustainability initiatives to reduce system wide energy consumption.

With an intention to "further improve the energy intensity performance," SEPTA partnered with smart grid firm Viridity Energy to additionally participate in the wholesale energy markets, and contracted ABB for the design, supply and integration of a "Wayside Energy Storage Project" using Saft's MAX 20P Intensium Lithiun-ion Battery Container.

The system was commissioned at the Letterly substation on the Market-Frankford Line in the Kensington Section of North Philadelphia in April 2012, and subsequently underwent a 6 month demonstration period up to the end of 2012.

While in operation since, this paper presents the results and performance achieved by the system for the recent period of October 2013, when the train regenerative voltage was raised from 735 V to 765 V, to April 2014 when this paper was produced.

System at Letterly substation

Recovering braking energy, an emerging industry trend

The concept of recovering the braking energy in transportation has been around for some time. Using „regenerative braking" to convert the kinetic energy of the vehicle into electricity, the transportation industries have progressively found ways to recycle this energy. Hybrid cars and buses, for example, can be up to 30 percent more fuel efficient than their combustion-only counterparts in urban environments.

Electrically powered trains also utilize regenerative braking, but since trains are not designed with on-board energy storage capacity as hybrid vehicles are, the regenerated energy from a braking train can only be used if there is another train accelerating in the immediate area. Otherwise, the energy is dissipated as heat into braking resistors.

This is why ABB introduced the ENVILINE™ ESS, a wayside energy storage system which connects to the catenary or third rail of an electric train system and captures this otherwise wasted braking energy. The ESS feeds the energy back to the trains, typically during their acceleration when demand is at its peak. Depending on the time of the day and frequency of trains, between 5 percent and 20 percent or more of the traction energy gets recovered as shown later in this paper.

Participating in the "smart grid" energy markets

In addition to recuperating the braking energy and lowering the cost and consumption of electricity, the ESS is designed to increase the economic benefit by additionally participating in the local energy markets as a "distributed energy resource". As confirmed by the results achieved so far, the revenues for this additional participation can exceed $200K on an annual basis, or 3-4X the value of the energy savings ($50-60K). This makes this additional contribution from the ESS not only beneficial to the local utility, but clearly financially attractive to SEPTA.

While it is predicted that all smart grids of the future will rely on some form of energy storage, including batteries for fast regulation and short peak shaving, few areas currently offer open market conditions for participating in the energy markets. In the Philadelphia area where SEPTA operates, PJM, the Regional Transmission Organization (RTO) mandated by the federal government to manage the reliability of the electric transmission system (the "grid"), allows electricity customers such as SEPTA to provide grid services with compensation. The storage system was designed with this in mind, and can participate in two key energy markets: frequency regulation and economic load response.

Frequency regulation

Frequency regulation helps balance generation and load to maintain the desired grid frequency. The system at the Letterly substation provides fast frequency regulation support into the PJM regulation market up to power levels of 800 kW by modulating the instantaneous consumption of the trains based on an automatic control signal sent by PJM.

Economic load response

The storage system is also designed to participate in PJM's economic load response program, which enables demand resources to respond to wholesale energy prices by reducing consumption and receiving a payment for the reduction.

Viridity Energy

A company which provides energy consumers with intelligent tools, software and services to interact proactively and productively with the electric grid in order to increase energy savings and create energy revenues, acts as SEPTA's curtailment service provider (CSP) for this project. In brief, Viridity's VPOWER™ software is used to optimize the participation of the ESS in the PJM wholesale electricity market which, in recent months, has been the fast frequency regulation service.

Viridity was instrumental in helping SEPTA develop the business model and predict the annual economic benefits which are achieved today.

Train and network information

The trains operating on the Market Frankford Line offer the following regenerative braking characteristics:

- Trains consisting of 3 married pair (MP) railcars, each with a maximum AW2 load weight of 164,540 pounds regenerating 16.3 mega joules (MJ) of energy back to the third rail;
- Dynamic braking, which starts at 50 mph and lasts approximately 15 seconds;
- The maximum regen voltage, set to 735 V dc at the start of the project in 2012, raised to 765 V in September 2013 and then to 790 V on April 01, 2014. The results of this paper reflect the performance with the regen voltage set at 765 V. A future release will follow and show the results at 790 V;
- Limited line current during braking of 2,750 A per MP.

The Letterly substation was chosen for the following reasons:

- There are five passenger stations within the study providing more than 1000 daily weekday train-stops;
- The calculated available braking energy is 3 kWh per married pair, 9 kWh per train;
- The substation features excess physical space for the pilot installation and potential expansion;
- Dual 13.2 kV AC commercial feeds, with three 3 MW rectifiers;
- 660 V dc nominal, with 690-695 V dc no load.

System architecture

Figure 1 below illustrates the block diagram of the system. The area shaded in light peach color represents the existing traction power system (TPS) of the Letterly substation. All dots shown in red represent measurement points of the site, and include the AC meters, the traction rectifier currents and the feeder breakers of the track sections and of the ESS.

The ESS consists of a power controller system (PCS) and 3 parallel DC-DC ENVILINE converters for a total power capacity of 2.2 MW. The Intensium (Lithium-ion) battery container of Saft Battery provides short term charge and discharge current capacity up to 1,600 A and storage up to 420 kWh.

The PCS receives high level control commands from Viridity's VPOWER™, including the PJM frequency regulation signal, and otherwise controls the operation of the system and provides status and performance information back to VPOWER.

This architecture enables the ESS to capture braking energy of trains which is returned from the track sections and, otherwise, to modulate the demand of the substation according to the PJM modulation signal.

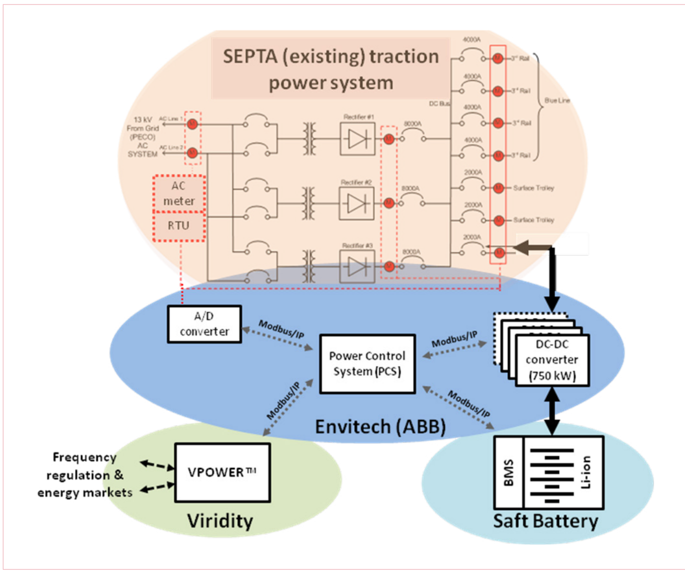


Figure 1: System block diagram of the SEPTA wayside energy storage system

Energy recovery results

The Market Frankford line is operated with 183 trains during weekdays, and 102 and 101 trains on Saturdays and Sundays. While one would expect to recover more braking energy during weekdays due to the higher frequency of trains, figure 2 shows that the opposite is actually happening.

During the eight weeks between September 21 and November 15, the system recovered an average of 1,284 kWh during weekend days, compared with averages ranging from 816 kWh to 994 kWh during the week days, or 40-50 percent more.

Figures 3 and 4 provide detailed profiles of the energy recovery for a typical week and weekend day, with figure 3a and 3b showing the size distribution of the regen events and figures 4a and 4b showing the profile as a percent of the total traction energy. For these two days, the total recovery was 1,140 kWh and 1,702 kWh.

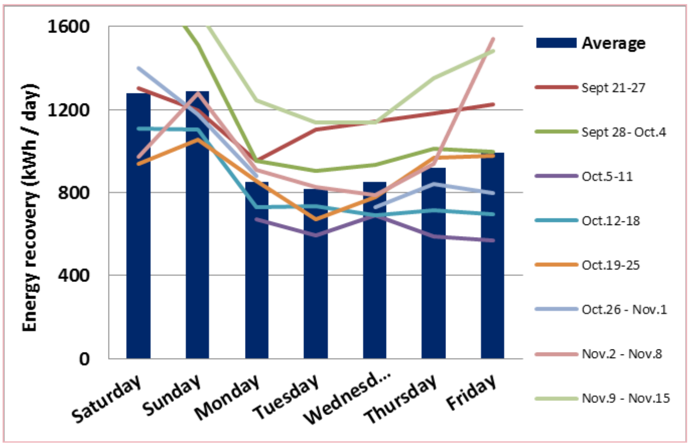


Figure 2: Recovered energy from September 21 to November 15, 2013 (trains set at 765 V)

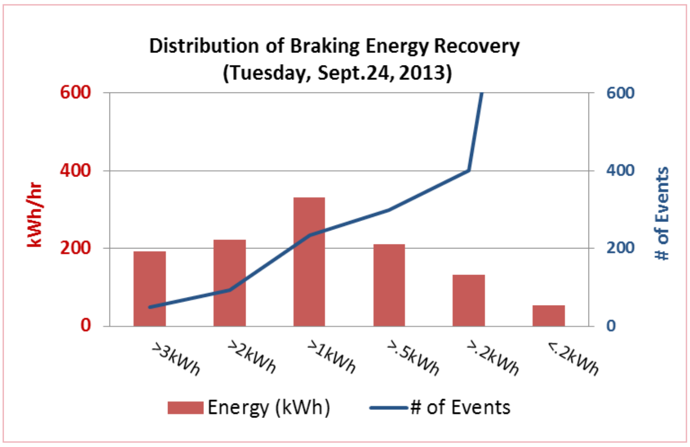


Figure 3a: Distribution of braking energy recovery by size and event count (Tuesday, September 24, 2013)

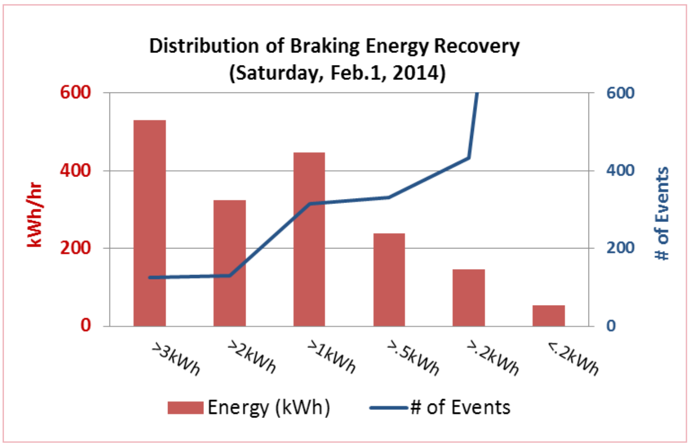


Figure 3b: Distribution of braking energy recovery by size and event count (Saturday, February 1, 2014)

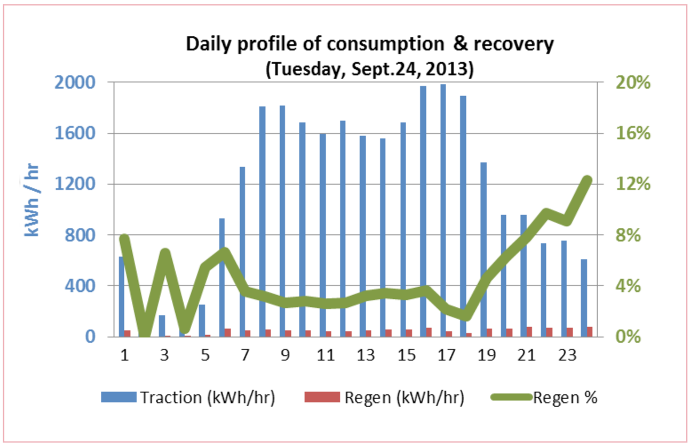


Figure 4a: Daily profile of braking energy recovery as percent of the traction power (Tuesday, September 24, 2013)

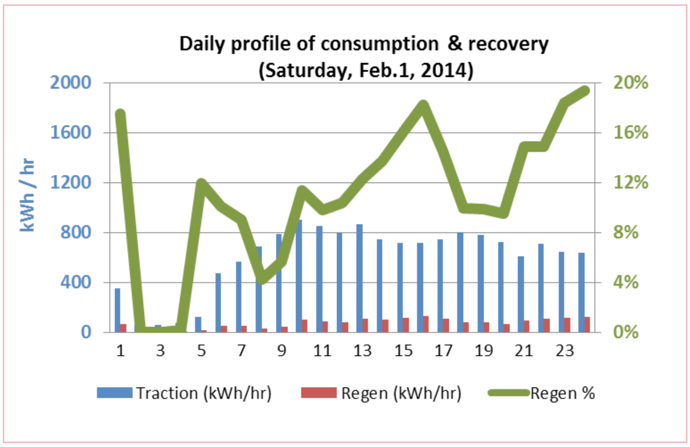


Figure 4b: Daily profile of braking energy recovery as percent of the traction power (Saturday, February 1, 2014)

From these results, we draw the following conclusions:

- While there are 183 trains per weekday and 102/101 trains per weekend day in each direction, the system recovers fewer large events than the frequency of trains, but also many more events in total. This is expected as many of the large local braking events get captured by other trains and because any braking at distant stations, any sudden deceleration along the track and any downward slope will also induce regenerated energy, albeit mostly in smaller events;

- In general, the rate of recovery drops under 5 percent of the traction energy during the peak hours when headways fall between 3-4 minutes, and increases to almost 20 percent when the headways increase to 12-15 minutes;

- The daily recovery can vary quite substantially from day to day and week to week. Because these are surface trains, weather also plays a major impact as heating can increase the consumption by 10 MWh or more on a cold day, which is equivalent to 50-60 percent of the normal traction load. As expected, this has a huge impact on the natural receptivity of the system, and consequently, on the resulting level of recovery.

Frequency regulation market results

The system is kept continuously in the market during most days, but at varying power levels based on the average load of the substation. This is because in frequency regulation, the system needs to respond by charging and discharging the battery proportionally to the dynamic regulation (RegD) signal from PJM.

In other words, the ESS needs to modulate the power demand of the substation proportionally to the value of the signal in order to help match generation with load and also maintain the desired frequency of the grid. But the ESS must perform this while maintaining the TPS voltage stable for proper train operation. During the initial demonstration of the system, tests were performed with various control signals to demonstrate the accuracy and speed of response by the ESS while keeping a stable TPS voltage. Figure 5 shows the results of one such test.

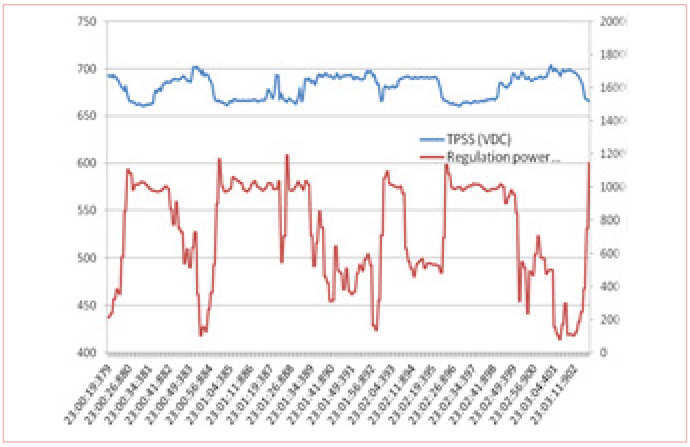


Figure 5: Response for frequency regulation

As can be seen by the levels of the blue bars in figure 4a, the hourly consumption of the substation during a weekday falls between 50-100 kWh/hour from 2-5 a.m. when train operations are stopped, then increases rapidly to peak above 1,600 kWh/hour during the day, and then progressively falls during late hours of service. During a weekend day (figure 4b), the pattern repeats but peaks around 800 kWh/hour due to the lower frequency of trains in service.

Because the ESS can only push energy up to what trains will consume, the system will participate in the market at power levels typically of 100 kW from 2-5 a.m., 800 kW from 5 a.m. to 11 p.m. during week days and 500 kW during weekend days, and at 400 kW otherwise.

Of course, the payout from PJM is proportional to the power level at which the system participates and to its performance score achieved, which varies typically between 70 percent and 90 percent, as can be seen in figure 6.

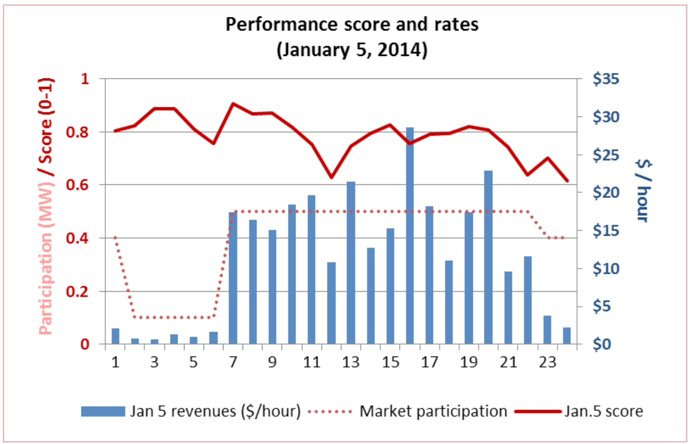


Figure 6: Daily performance in the frequency regulation market

While figure 6 shows the results of a typical day during which temperature conditions are moderate, the market rates for frequency regulation will fluctuate with offer and demand, and increase significantly during extreme weather conditions. This can be seen in figure 7 which shows the results during the studied period between October 2013 and April 2014.

While the first two months can be considered representative of spring and fall months during which temperatures of mostly mild, the following winter months show how lucrative the frequency regulation market can be under harsh weather conditions, delivering total revenues well in excess of $100k, revenues which are incremental to the energy savings achieved by the recovery of the train braking energy.

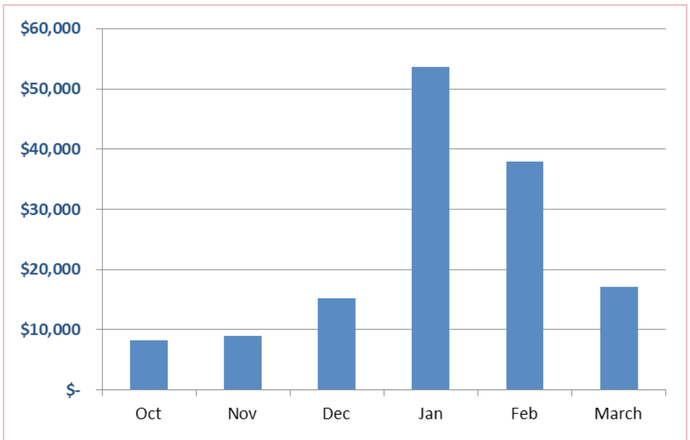


Figure 7: Financial results from the frequency regulation market from October 2013 to March 2014

Reliability and life expectancy

Some of the key considerations in the evaluation and decision to deploy an energy storage system are its reliability and life expectancy, along with risk of interference with the train network and operation. This is because improving the energy efficiency and delivering additional revenues is important, but secondary to the reliability and safety of train operations.

With regards to reliability and life expectancy, the ESS system deployed at Letterly is designed to achieve minimum operating life of 20 years for the power electronics and 15 years for the battery. Since its initial startup in April 2012, and subsequent start of commercial operation on October 1st 2012 as an approved asset on the PJM network, the system has experienced only a few disruptions, mostly caused by software issues and affecting only minor ancillary components (contactors, switches and flash memory chips). Overall, the system has not sustained any failures of its major power electronic components and battery modules. Since the last software upgrade in the summer of 2013, the system has also not experienced any disruption in service.

As for the risk for interference with the train operation, two considerations are essential, one that the system must not interfere with the signaling and communications and, otherwise, that it must not induce a failure or malfunction of the trains and other equipment in case of a system fault.

With respect the first consideration, the potential interference in the frequency band of the signaling and communications, this was verified early during the design phase and tested for during the initial off-hour commissioning tests. This is a necessary step of any project given the different signaling systems and trains in services across the different transit authorities.

As for the possibility of inducing a failure or malfunction from a fault, because the storage system is designed to operate in parallel and independently from the existing traction power system, shutting it down will simply leave the trains and network operating as they were before the project. Also, in case of a critical fault such as a short circuit, the system is designed to shutdown instantly and prevent over voltage or under voltage conditions from appearing and affecting the operation of the train.

The results seen during the first two years of operation have indeed shown that the normal operation along with the minor disruptions experienced have had no adverse effect on the operation of the trains.

Lessons learned and improvements

Despite the clear success of the Letterly project, ABB and SEPTA identified opportunities for improving the amount of braking energy recovered by the system along with the performance score in the frequency regulation market. These improvements would further increase the energy savings and revenues from the energy market.

Figure 8 shows the current captured by the ESS during a single braking event. Despite the higher current capacity of the converters, the maximum battery charge current is 1,600 A, which corresponds exactly to the level seen on the curve, and which leaves the energy represented by the area shaded in blue unrecovered and consequently dissipated by the on-board resistors of the train.

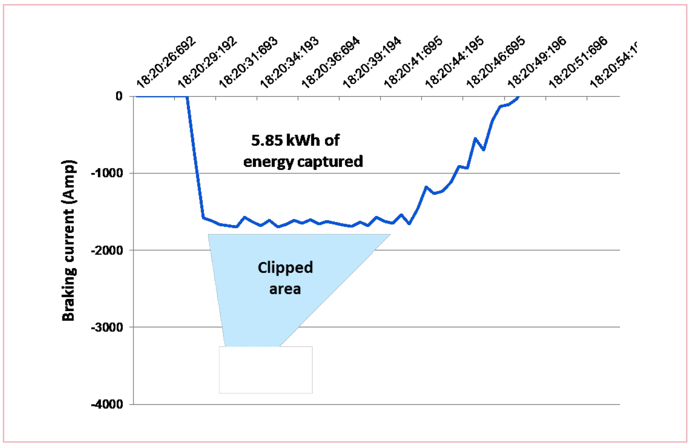


Figure 8: Clipping from the charge current limitation during a single braking event

A storage media with a higher charge capacity would push the blue line further down and reduce the clipping area, resulting in more energy recovery and less resistor dissipation. While this clipping occurs mainly on braking events coming from the local and immediately adjacent stations, and also mainly during off-peak hours when receptivity is low, it is estimated that 15- 20 percent additional energy could be recovered with a storage media having a higher charge capacity.

The second opportunity for improvement is with the performance score in the frequency regulation market. The table in figure 9 provides the distribution of the energy recovery for September 24, 2013, the same day presented before in figures 3a and 4a. In this table, we highlight the time during which the system is handling the braking energy, which totals 3.27 hours over the entire day.

Tuesday Sept 24 2014	>3kWh	>2kWh	>1kWh	>.5kWh	>.2kWh	<.2kWh	Total
# of Events	49	92	235	299	400	1645	2720
Energy (kWh)	192	222	331	211	132	52	1140
Regen time (hours)	0.26	0.34	0.65	0.55	0.53	0.95	3.27
Average kWh / event	3.92	2.41	1.41	0.70	0.33	0.03	0.42

Figure 9: Distribution of the energy recovery and regen time

To achieve a higher performance score and resulting payout from frequency regulation, the system must switch from recovering braing energy to responding to the RegD signal of PJM as quickly as possible. This is achieving by finding the optimum the operating settings of the system which provide the right balance between capturing maximum surplus energy and achieving the maximum frequency regulation revenues.

However, because the ESS is constructed with a single storage media, it operates in one of the two modes, but never both at the same time. From figure 9, it is seen that the ESS was taken away from the RegD signal to capture braking events which are smaller than 0.5 kWh for 1.48 hour, and yet captured only 184 kWh during that time. While capturing braking energy provides a positive financial and environmental contribution, 45 percent (1.48 hour) of the total braking energy capture time returned only 16 percent (184 kWh) of the total recovery.

A different architecture which could simultaneously capture the braking energy events and modulate the load of the substation according to the RegD signal would deliver the savings and significantly improve the performance score and revenues of the frequency regulation market.

These two considerations, i.e. the desire to increase the energy recovery with better current capture capacity and to improve the performance score, are the reasons ABB opted to combine super capacitor with battery storage media in a unique hybrid configuration in the scope of a second project to be rolled out later this year.

A transformative impact

In an era of rising energy prices, the transportation industry, which by its nature will always be energy intensive, must take actions to avoid becoming more financially strained.

SEPTA's "Wayside Energy Storage Project" introduces a new paradigm and demonstrates the extent to which energy can be leveraged and can provide financial benefits and better sustainability. This project has the potential to transform the way that the transit industry thinks about energy by making transit agencies not only energy consumers, but also energy producers and full participants in the smart grid market of tomorrow.

As a whole, SEPTA's energy storage initiatives will support its sustainability program goal of reducing energy intensity, defined as energy use per passenger mile, by 10 percent by 2015.

Additional credit and references

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