Utilizing Wayside Energy Storage Substations in Rail Transit Systems – Some Modelling and Simulation Results

J.G. Yu, PhD
SYSTRA Consulting, Inc
Philadelphia, PA

Martin P. Schroeder
American Public Transportation Association
Washington, DC

David Teumim
Teumim Technical, LLC
Allentown, PA

Keywords: DC Traction Power Systems, Energy Storage Devices, Wayside Energy Storage Substations, Computer Simulation; Energy Savings.

Abstract

The APTA / EPRI Energy Storage Research Consortium [1] study team, funded by the Transportation Research Board TCRP program, conducted a study of wayside energy storage systems coupled with track propulsion networks of actual system designs. Adding energy storage is aimed at reducing energy consumption through improved capture of regenerative braking energy, reduced energy costs through reduction of peak power demand, improvement of power quality through low-voltage support, and use of energy storage systems as supplements to or replacements for conventional electrical substations under specific conditions. Computer simulations are performed to assess the benefit of wayside energy storage systems starting with a look at voltage support.

Introduction

Energy storage devices (ESD) for transit may take different forms, such as flywheels, batteries, electrochemical capacitors, or hybrid devices (batteries combined with electrochemical capacitors, and other variations). Such devices have seen rapid development in recent years. Their applications have spread from traditional roles as small scale Uninterruptible Power Supplies (UPS) to utility scale storage devices.

In DC-traction power systems, wayside energy storage substations (WESS) using ESD are emerging as a viable supplement to traditional substations for traction power system designers. A WESS can be located on its own anywhere along the track, without the need of medium voltage power supply sources from the utility. However, it is also recognized that a WESS can be tied to an AC utility supply using DC/AC inverters should there be interest in sharing the benefits of storage between transit systems and utilities, both sharing similar needs in power quality and peak power reduction. The systems studied here however, only address a DC connected WESS. The following discussion will focus on the potential benefit of ESD-substations to correct voltage support problems and improve capture ratio of available regenerative braking energy. Results will also highlight how various general design parameters affect the performance of energy storage systems.

1 A Typical WESS Design

The main components of a WESS installation and a traditional rectifier substation are compared in the following figure.

Figure 1: Comparison of the main components between a rectifier substation and a WESS

The core components of most wayside energy storage substations consist of a storage medium and a power control unit, as well as the necessary DC bus and switchgear for...
power distribution to the track, third rail or overhead contact systems (OCS).

Control of WESS charging and discharging cycles is based on voltage levels as shown in Figure 2.

![Figure 2: Power control diagram for WESS](image)

The main parameters that define a WESS design are:
- Energy storage capacity (kWh)
- Power rating (kW)
- Power conversion efficiency
- Maximum current (charging or discharging) (amps)
- Control voltage (Vc) and various other voltage levels for charging and discharging control (volts)

Computer models have been developed that include these energy storage device parameters [^2] and the associated constitutive power distribution models of the traction power systems. Computer simulations predict full-system operating behaviour, energy storage performance and establish the degree of sensitivity to various system design parameters. Additional general system parameters used in simulations included variables defining electrical performance of circuit breaker houses and substations, electrical resistances of third rail and return rail, substation capacity, track alignment data, vehicle braking and propulsion capabilities, and operational data such as train headway scheduling, station dwell times, off-peak operating changes, and various other parameters.

To further identify optimal locations of energy storage devices within the alignment of candidate conventional propulsion system designs, simulations without energy storage are conducted first to establish potential weaknesses within the system associated with problems of voltage sag or regenerative braking energy capture. This type of analysis was conducted for three families of rail systems including light rail, heavy rail and commuter rail. From these families, representative system designs were chosen and energy storage systems sized based on simulation results, energy storage characteristics, and analysis of data taken from actual operating transit agencies.

Simulations were performed on three representative systems organized. For each system, simulation results predicted performance of the overall system as well as the energy storage benefit.

**Light Rail**

**System parameters**

The main parameters of the light rail transit (LRT) system being simulated are listed as follows:
- 7 Miles of track (double track system)
- 12 Stations
- 750V nominal voltage DC traction power system
- 7 Traction power substations (TPSS); each equipped with 1.5MW rectifier unit
- 1 Circuit breaker house (CBH)
- 2 car trains in operation with regenerative braking
- 5 Minute headway in peak hours
- 15 Minute headway in off peak hours and weekends

The following figure shows the motoring and regenerative braking control diagram for a typical LRT vehicle.

![Figure 3: Power control diagram for the LRT vehicle](image)

**Train voltage support requirement**

Train voltage is a critical performance parameter for the traction power system. For this particular system, when a train’s voltage falls below 575V (see Figure 3) corresponding to a voltage sag condition, the train’s power demand cannot be fully met by the traction power system, which will have an adverse impact on the performance of the train. At or below 500V, the train’s traction power motor will be shut down in order to avoid damage to the equipment.

Under normal conditions (when all substations are in service), the simulated train voltages are all above 575V, which are adequate for trains to achieve their on-time performance. However, when the rectifier in positions A4 or A5 TPSS is out of service, the minimum train voltage can fall to 504V and 559V respectively. These sags are shown in the following...
In order to avoid the excessively low voltage conditions when the rectifier in A4 or A5 TPSS is out of service or has failed, either a full rectifier substation or a WESS at A4X-CBH location can be considered as a reinforcement. Addition of energy storage (WESS) will help support the voltage sag and provide a potential energy saving benefit by improving capture of regenerative braking. This simulation and analysis process, by which we begin with a look at voltage support first and energy saving second is carried throughout the various mode analyses.

New WESS option

Returning to the example above, if an appropriately sized WESS is installed in location A4X, the resulting train voltage improvements can be shown in Figures 6-7, given that rectifiers at positions A4 or A5 TPSS are removed.

<table>
<thead>
<tr>
<th>Case #</th>
<th>Scenario</th>
<th>A4X Type</th>
<th>Minimum Train Voltage (V)</th>
<th>Voltage Improvement (V)</th>
<th>ESD Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
<td>A4 outage</td>
<td>CBH</td>
<td>504</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>74b</td>
<td>A4 outage</td>
<td>ESD (Vc=760V)</td>
<td>588</td>
<td>84</td>
<td>3.1</td>
</tr>
<tr>
<td>84</td>
<td>A4 outage</td>
<td>TPSS</td>
<td>605</td>
<td>101</td>
<td>n/a</td>
</tr>
<tr>
<td>65</td>
<td>A5 outage</td>
<td>CBH</td>
<td>559</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>75b</td>
<td>A5 outage</td>
<td>ESD (Vc=760V)</td>
<td>630</td>
<td>71</td>
<td>3.7</td>
</tr>
<tr>
<td>85</td>
<td>A5 outage</td>
<td>TPSS</td>
<td>632</td>
<td>73</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Note – ESD power rating at 1500 kW
WESS parameters

With the installation of the WESS in location A4X, the system’s receptivity (the ratio of utilized regenerative energy over the total available regenerative energy) will also be improved, resulting in a greater potential to recover regenerative braking energy. As a result, the energy saving ratio due to regenerative braking (the ratio of energy consumption with regenerative braking over the energy consumption without regenerative braking) can be improved.

When all substations are in service and we do not experience a voltage sag problem, we can take a different look at the effect of energy storage, principally to save energy. The control voltages of the WESS may be adjusted to best optimize energy saving rather than providing voltage support, thus maximizing the capture of regenerative energy. So, when voltage support is not needed, an adjustment in the voltage settings of the WESS can be made for optimal energy saving. Table 2 compares system-wide energy saving potential resulting from variations in WESS control voltages. This table also demonstrates the corresponding energy and power rating requirements for the WESS. An electricity cost saving analysis utilizing this strategy is undertaken in the next section.

<table>
<thead>
<tr>
<th>Case #</th>
<th>A4X Type</th>
<th>Receptivity (%)</th>
<th>Energy Savings (%)</th>
<th>ESD Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>CBH</td>
<td>83.6</td>
<td>29.9</td>
<td>n/a</td>
</tr>
<tr>
<td>70a</td>
<td>ESD (Vc=720V)</td>
<td>84.1</td>
<td>30.1</td>
<td>0.20</td>
</tr>
<tr>
<td>70b</td>
<td>ESD (Vc=760V)</td>
<td>84.5</td>
<td>30.2</td>
<td>1.30</td>
</tr>
<tr>
<td>70c</td>
<td>ESD (Vc=793V)</td>
<td>88.0</td>
<td>31.5</td>
<td>2.30</td>
</tr>
<tr>
<td>80</td>
<td>TPSS</td>
<td>83.3</td>
<td>29.8</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Note - All TPSS in normal operation

Electricity cost saving analysis

We have shown that a WESS can effectively mitigate problems associated with low train voltages. To examine the potential energy and cost saving benefits of energy storage, a simple electricity cost analysis can be performed using the options noted above. We start with a comparison of the 15-minute power averages across all substations in the system under normal operation with and without a WESS, as shown in Table 3. The 15-minute averages are used because of the correlation with utility peak power charging average time periods, which are in most cases 15-minutes.

From the table it can be seen that the 15-minute average power in each substation for 5-minute headways represents the peak power demand, while 15-minute headways are less as measured over the same 15 minute period. What this table shows is the utility supplied power to each substation along the alignment. Higher power requirements are shown near the WESS because there is no supply at that point and neighbouring substations would need to provide the additional power to charge the WESS, although only marginally. Both the 5-minute and 15-minute headway conditions are used to compute the overall energy saving in a 24 hour period. More specifically, the following 24-hour train operation schedules are assumed:

- 5-minutes in peak hours (6-10Am and 4-8PM)
- 15-minutes in off-peak hours and weekends
- No train service between 1AM and 4AM on any day

Using actual published electricity tariffs from a USA utility company [3], the annual cost for each substation is calculated based on individual traction substation billing arrangements and the power demands noted in Table 3. These are listed in Table 4.

Table 4 indicates that the WESS installation will have an annual electricity cost benefit of $45,000 (based on the current tariffs) compared against a full rectifier installation in the A4X location. Additional cost benefits may be possible because a WESS is typically less expensive than a full rectifier utility substation.
Table 4 Summary of Annual Electricity Cost Saving due to WESS (all figures in US $)

<table>
<thead>
<tr>
<th>Substation</th>
<th>With A4X-TPSS</th>
<th>With A4X-WESS</th>
<th>Savings with WESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>$182,342</td>
<td>$184,763</td>
<td>$-2,422</td>
</tr>
<tr>
<td>A2</td>
<td>$202,057</td>
<td>$207,687</td>
<td>$-5,630</td>
</tr>
<tr>
<td>A3</td>
<td>$173,973</td>
<td>$181,808</td>
<td>$-7,835</td>
</tr>
<tr>
<td>A4</td>
<td>$172,945</td>
<td>$183,581</td>
<td>$-10,637</td>
</tr>
<tr>
<td>A4X</td>
<td>$93,875</td>
<td>$0</td>
<td>$93,875</td>
</tr>
<tr>
<td>A5</td>
<td>$161,894</td>
<td>$172,907</td>
<td>$-11,012</td>
</tr>
<tr>
<td>A6</td>
<td>$181,397</td>
<td>$189,110</td>
<td>$-7,713</td>
</tr>
<tr>
<td>A7</td>
<td>$159,353</td>
<td>$162,810</td>
<td>$-3,456</td>
</tr>
<tr>
<td>Sum</td>
<td>$1,327,835</td>
<td>$1,282,666</td>
<td>$45,169</td>
</tr>
</tbody>
</table>

Metro Rail

System parameters

A similar simulation analysis, again looking at the conditions of low voltage and regenerative braking energy, is performed for a heavy rail (subway) system using the simulation parameters below.

- 5 Miles Metro System; 4 Stations
- 700V DC traction power system
- 4 Traction substations
- 2 Circuit breaker houses (CBH)
- 8 Car trains with regenerative braking
- 2 Minute in peak hours (AM & PM)
- 5 Minute headway in mid day hours
- 15 minute headway in off peak and weekend operations

To set up the model, Figures 8-9 show the motoring and regenerative braking control diagram for a typical metro rail vehicle and the conditions of low voltage. Simulations will utilize these characteristics. For this case, sensitivity analyses are performed to characterize the influence on system design parameters on overall energy storage performance.

Simulation results indicate that there will be low voltage occurrences at the east end of the track, as shown in Figure-9.

The effect of ESD power rating

If an ESD is installed at position G05B at the east end of the track, the low voltage conditions will be improved. A 3MW installation is required to achieve 525V or better, as shown in Figure 10.

A larger installation of 4MW will achieve an even better result. Simulated load and energy cycles for the ESD are shown in Figures 11-12.
Minimum train voltages and system receptivity (the ability to accept regenerative power) under different installations at different headway offsets are shown in the following figure.

Many factors affect the system receptivity and energy saving figures, such as track alignment, passenger station locations, electrical parameters of the traction power system, vehicle characteristics, train operational characters (acceleration and braking rates, coasting, offsets in headway dispatches on the two tracks, timing deviation from regular headways, etc.). The figures contained in this paper represent nominal conditions. Variations from these figures can be expected when system conditions change, but such detailed comparative analyses are beyond the scope of this investigation. However, the following sections illustrate the general impact on system performance given such variations.

### The effect of headway offset

For peak hour operation (2 minute headway), simulations were carried out for different offsets between east and west bound train’s dispatching timing (headway offsets). Such offsets result in the trains meeting at different locations, which in turn affect the train voltage and other conditions in the system. Time-distance plots for three different headway offsets on west bound trains are illustrated in the following figure.

### The effect of voltage limit

Receptivity variations versus voltage limits are shown in the following figure.

Many factors affect the system receptivity and energy saving figures, such as track alignment, passenger station locations, electrical parameters of the traction power system, vehicle characteristics, train operational characters (acceleration and braking rates, coasting, offsets in headway dispatches on the two tracks, timing deviation from regular headways, etc.). The figures contained in this paper represent nominal conditions. Variations from these figures can be expected when system conditions change, but such detailed comparative analyses are beyond the scope of this investigation. However, the following sections illustrate the general impact on system performance given such variations.
The effect of headway

Receptivity variations versus headways are shown in the following figure.

Energy cost savings

The estimated annual cost for the track section and cost savings[^3] under different options are shown in Table 5.

Table 5 Summary of Annual Electricity Cost Savings
(All figures in US $)

<table>
<thead>
<tr>
<th>Substation</th>
<th>CBH</th>
<th>3MW Sub</th>
<th>3MW ESD</th>
<th>4MW ESD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total annual cost</td>
<td>$4,874,350</td>
<td>$4,831,516</td>
<td>$4,776,365</td>
<td>$4,760,599</td>
</tr>
<tr>
<td>Savings over 3MW Sub Option</td>
<td>-$42,833</td>
<td>$0</td>
<td>$55,152</td>
<td>$70,917</td>
</tr>
</tbody>
</table>

Commuter Rail

A 5 mile section of a commuter rail system is simulated to assess the feasibility of WESS as an alternative to the traditional rectifier substation for train voltage support. The no-load voltage is at 720V and the nominal voltage 685V. Regenerative braking is not applied for this system as most commuter rail vehicles are incapable of braking regeneration. Train voltage plots under different options at location MP-35 are shown in the following figures.

The effect of ESD control voltage

Adjusting the control voltage (Vc) of an ESD installation will achieve different levels of train voltage improvement. On the other hand, high levels of voltage improvement demand higher power ratings and larger energy capacities for the device.

Due to the distances between the ESD and the nearby substations, the charging rate can be limited by the circuit
resistances. Higher Vc setting can have better improvement of train voltages. However, this needs to be balanced against the requirement to maintain sufficient energy rate to keep the device at desired capacity, so that there is sufficient energy content for the next discharging cycle.

The following figure shows the load cycle under different control voltages. The same figure also illustrates the charge rates limited by the electrical circuits, between 1.6 and 1.8 MW.

![Simulated ESD Load Cycle](image)

**Figure 21: ESD load cycle under different control voltages**

The maximum charging and discharging rates and minimum train voltages are compared in Table 6.

<table>
<thead>
<tr>
<th>ESD Control Voltage</th>
<th>Vc=650</th>
<th>Vc=660</th>
<th>Vc=670</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. MW Output</td>
<td>3.2</td>
<td>3.6</td>
<td>3.8</td>
</tr>
<tr>
<td>Max. kWh Usage</td>
<td>31.7</td>
<td>37.5</td>
<td>42.4</td>
</tr>
<tr>
<td>Minimum Train Voltage</td>
<td>518</td>
<td>529</td>
<td>536</td>
</tr>
</tbody>
</table>

**Table 6 ESD Rating and Capacity vs. Voltage Improvement**

**Summary**

This paper presented simulation results for three systems with potential applications of a WESS as an alternative to traditional rectifier substations for train voltage support. ESD power ratings and energy capacities vary with the systems and the desired levels of voltage improvement, as shown in Figure 22.

**Figure 22: ESD energy capacity versus system type and power rating**

For two of the systems where regenerative braking is used, there is added energy saving benefits of an ESD option. It should be expected that the annual savings will increase in the future as the electricity tariffs tend to go up in line with general energy cost increases.

**Acknowledgements**

The authors thank Mr. Larry Goldstein, Senior Program Officer for ACRP and TCRP, Transportation Research Board, for his support with the study. The authors also thank all the transit agencies, government agencies and vendors of the APTA/EPRI Energy Storage Research Consortium for their generous involvement and support of the project. The simulation results presented in this paper were obtained by using SYSTRA’s RAILSIM® Load Flow Analyzer.

**References**

