On Board Energy Storage for Light Rail Vehicles

Thomas Heilig and Jason Grohs

Tri-County Metropolitan Transportation District of Oregon

Portland, OR

BACKGROUND INFORMATION

TriMet Light Rail System

Since opening its first light rail line in 1986, Portland's MAX has expanded into a 52-mile regional rail system with four lines and more than 100,000 daily riders. An additional 7.3 mile extension is currently under construction and slated for opening in September 2015.

TriMet currently operates four generations of light rail vehicles. All cars are approximately 90 ft long, single or double articulated, have six axles and are designed for boarding from low-level (ten inch) platforms. They are operated mostly as two-car consists, since the short (200 ft) blocks in downtown Portland prevent operation of longer trains.

26 Type 1 high floor cars entered service in 1986, built by Bombardier in Barre, Vermont. Switch resistor propulsion technology allows for dynamic braking, but not for regeneration and recovery of braking energy.

Three generations of low-floor cars were introduced since, starting in 1997 with the opening of the Westside Line. All are using modern ac propulsion systems, allowing for regeneration into the line and energy recovery. Today, 101 low floor cars are in service, bringing the total number of LRVS on TriMet's system to 127.

The traction power system is nominally 750 Vdc, supported by 54 substations. Most substations are rated at 1 MW capacity, except the fifteen oldest ones, which are rated at only 750 kW. The system is divided into two electrically isolated segments. The larger eastern segment is set at 825 V full load / 875 V no load. The western segment has a lower system voltage, 750 V full load / 795 V no load. Substations use simple rectifiers that cannot feed energy back to the utility.

A large scale study in 2002 concluded that regeneration reduced TriMet's annual energy cost by approximately 24% or $900,000 at the time. With increasing mileage and increasing energy cost, estimated annual savings have almost doubled to approximately $1,700,000 annually since.

Data collected in 2010 showed that the overall efficiency of regeneration on the TriMet system was approximately 70%. More precisely, 70% of the total available brake energy was already captured and used by trains on the system, with the remaining 30% lost and converted to heat by brake resistors.

Project Background

In 2010, TriMet received an FTA TIGGER II (Transit Investment for Greenhouse Gas and Energy Reduction) grant for $4.2M to install on-board energy storage units on approximately 20 Light Rail Vehicles (LRVs) to maximize regeneration efficiency.

TriMet's concept envisioned units with approximately 1 kWh capacity, using super capacitors for energy storage. The Type 3 vehicle fleet was targeted for installation as they offered sufficient space on the roof for placement of a new unit, and could accommodate the added weight.

A Request for Proposal outlining TriMet requirements was issued in March of 2011, with a contract awarded to American Maglev Technology, Inc (AMT) from Marietta, Georgia in June of the same year.

ENERGY STORAGE SYSTEM (ESS) DESIGN

AMT offered a 1kWh unit design based on Double Layer Capacitors (DLCs), using a bi-directional buck/boost chopper to match DLC stack voltage to traction line voltage. Figure 1 shows the basic single line diagram for the system.

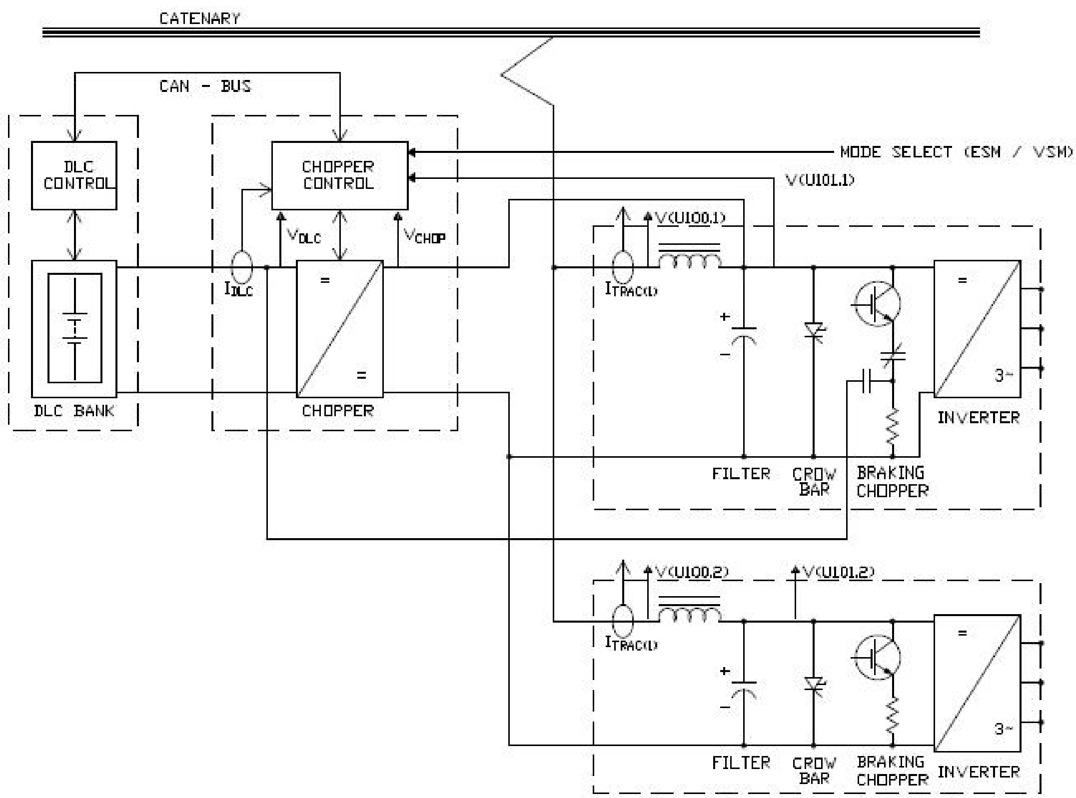

Figure 1. Single Line Diagram of System

Arrangement

In this original arrangement, the DLC bank and its control unit are packaged in a single enclosure, and the IGBT chopper and its associated controls, including line and discharge contactors, are mounted in a separate enclosure.

The high voltage connection to the vehicle is made at one of the vehicle's propulsion containers, thus eliminating an additional line filter and its associated weight. The brake resistor is used to discharge the capacitor bank for maintenance purposes.

Modes of Operation

The system is designed to operate in one of two modes, Energy Saver Mode (ESM) or Voltage Stabilization Mode (VSM). In ESM mode the DLC bank is kept discharged in order to be receptive to excess regenerated braking energy. The energy recovered is quickly supplied to any receptive user once the line voltage drops to a level where it is receptive to the energy. In VSM the DLC is kept charged in order to supply energy to stabilize the overhead voltage supply during low line voltage conditions or line voltage interruptions. We anticipate use of the VSM during the threat of freezing rain events which will allow vehicles a means to operate past sections of overhead contact wire that are iced over.

Prototype

A prototype unit was manufactured based on the design concept and was installed on a LRV for testing in the Fall of 2011. Main technical data of the prototype unit is shown below:

Line Voltage Range	525 – 925 Vdc
Charge/Discharge Power Rating	120 kW
Charge/Discharge Current Rating	240 A
Peak Current	420 A
DLC Voltage Operational Range	250V – 500V
Usable Energy	1.221 kWh
Weight	630 kg

Testing included running the system in ESM as well as VSM and viewing the system and vehicle performance real time. Testing of the retrofitted LRV on the mainline during revenue service allowed the parameters controlling the charging and discharging curves to be adjusted to optimize the performance of the system. These parameters were set at a level that would allow the ESS charging curve to be activated just before the vehicle's brake inverter was fired sending excess regenerated braking energy to the brake resistors.

After an abundance of static and dynamic testing and fine tuning of the system parameters the ESS equipped LRV was released back into revenue service.

Initial Results

After running the system in revenue service for approximately 3 months, data collected was analyzed to audit performance. What was realized was that the full capacity of the 1.221 kWh capacitor bank was only fully utilized on certain segments along the track alignment where the conditions were optimal. These segments were mainly high speed sections of track with station spacing of approximately 3 km with lower train density. Operation on these segments allows the vehicles to quickly decelerate into stations from higher speeds leading to high regeneration rates, but with the absence of available users for the regenerated energy, the DLC bank was able to realize its full potential and charge to capacity. This optimal scenario only accounts for roughly ¼ of the total operation meaning the full capacity of the energy storage system was only being utilized on a small portion of the alignment. Refer to Figure 2 for as sample of the data collected and analyzed.

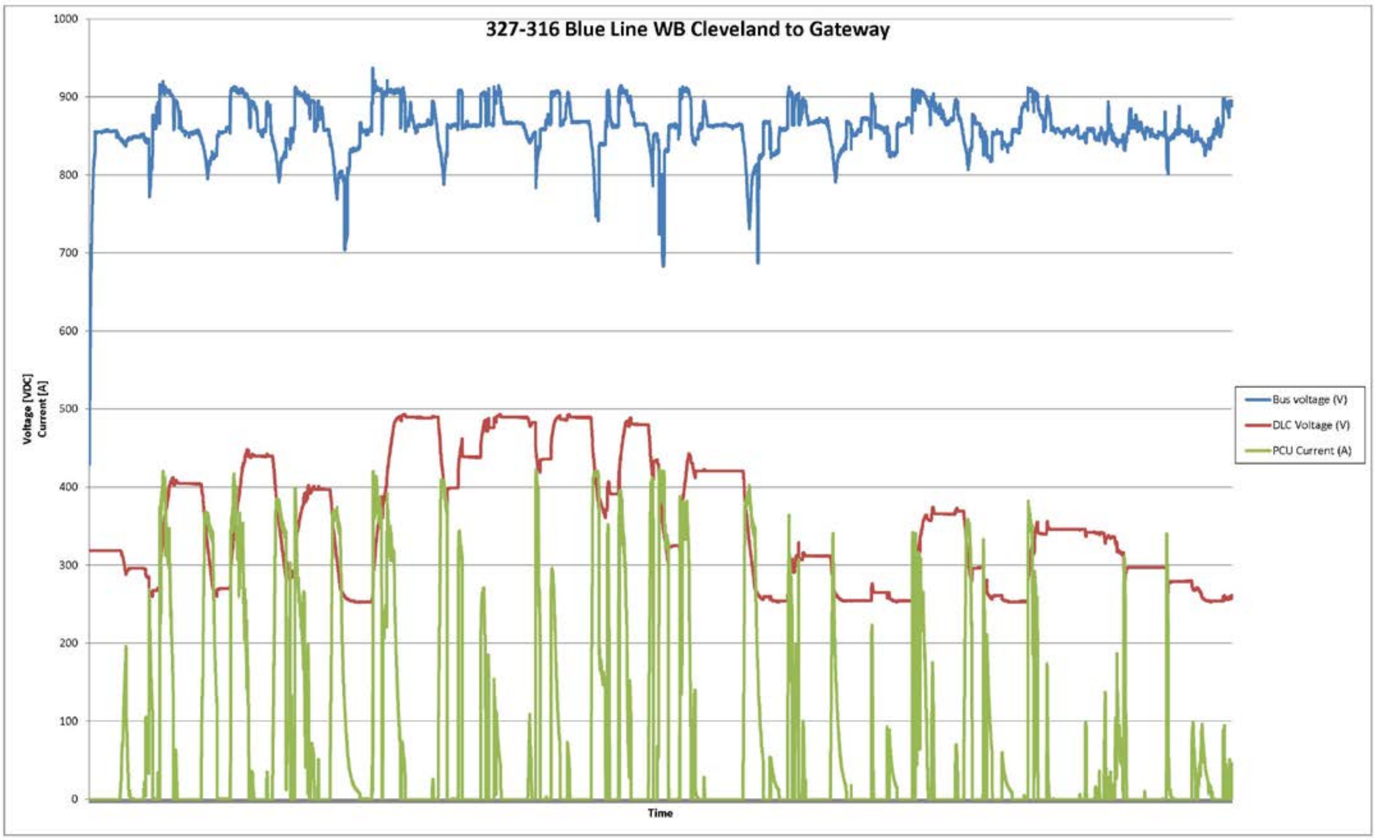

Figure 2. ESS Operational Data

RE-SIZING OF UNIT

Using the findings of the data collected for the prototype unit as a basis, it was evaluated whether a capacitor bank with a reduced capacity would better suit the application. From this evaluation a revised lower capacity system was developed that would allow a more compact, lighter-weight unit to be installed. Due to the reduction in storage capacity there was a monetary savings from the original cost of each unit, allowing additional LRVs to be retrofitted (27 instead of 20 as originally proposed). An added benefit to a lighter-weight, more compact unit was the ability to distribute more receptive units across the system, increasing overall efficiency and energy savings.

Production Units

After a re-design effort, a revised unit was developed. Main technical data of the final production units is shown below:

Line Voltage Range	525 – 925 Vdc
Charge/Discharge Power Rating	120 kW
Charge/Discharge Current Rating	240 A
Peak Current	420 A
DLC Voltage Operational Range	250V – 500V
Usable Energy	0.814 kWh
Weight	550 kg

The capacitor bank consists of 384 Maxwell BCAP 3000 capacitors, arranged in 12 modules connected in series. Each module consists of 2 parallel stacks of 16 capacitors connected in series, shown below in Figure 3. This works out to a total energy content of 1.09 kWh at the maximum voltage of 500 Vdc. Minimum operational voltage of the capacitor bank is 250 Vdc, resulting in a useable energy content of 0.814 kWh.

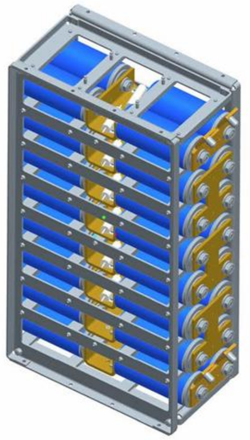

Figure 3. Capacitor Module Assembly

Arrangement

The system was revised to package all components into a single enclosure reducing the overall footprint of the equipment on the LRV roof. The IGBT based inverter, along with the integrated overvoltage line contactor, was packaged to fit within the main enclosure in the area that was vacated by the removal of approximately 1/3 of the double layer capacitors. See figure 4 for a layout model of the unit.

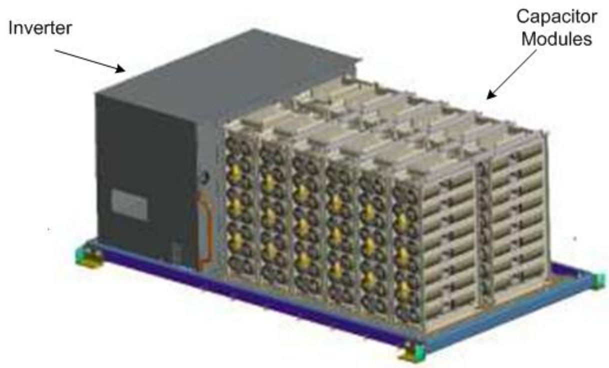

Figure 4. ESS (Shown without enclosure)

Installation

The modular design of the production energy storage system units helped to reduce the amount of equipment necessary for installation from three enclosures to one. Limiting the number of enclosures allowed a reduction in the amount of interconnect wiring simplifying the install. Installation basics include, mounting of the ESS enclosure, routing of both high voltage and low voltage wiring, installation of a user interface control panel and modification of existing equipment for integration of the unit to the existing vehicle main circuitry.

Testing

To ensure each ESS installation was properly integrated with the LRV, full static and dynamic testing was performed. After all wiring was verified, static testing was performed by cycling the charge of the capacitor bank in VSM. The bank was charged to full capacity, forcing the DLC balancing circuitry to activate, regulating the charge of the stacks. Verifying manual discharge through the vehicles braking resistors was also performed to validate the ability for maintenance personnel to safely discharge the capacitor bank. After verification of static functionality each vehicle was moved to a test track to undergo low speed dynamic testing for both ESM and

VSM. ESM testing consisted of low speed acceleration and braking cycles to ensure the system would charge and discharge properly as well as verifying the integration of the ESS did not adversely affect the performance of the vehicle propulsion systems. VSM testing was performed to verify the vehicle could draw from the ESS with low overhead line voltage levels. This was simulated by manually lowering the pantograph from the overhead catenary, isolating the ESS as the only power source, and operating the vehicle down the test track.

Upon completion of testing for each retrofitted vehicle, it was placed back into revenue service. Energy statistics were taken for each vehicle before incorporation of the ESS to allow the effect of addition of the ESS on the overall vehicles regeneration recovery efficiency to be tracked. Samples of the energy statistics are then taken periodically and compiled to track the performance of the ESS.

Results

Initial results on the performance of the final production units after a few months of running data show that the efficiency of the vehicle's ability to recapture regenerative braking energy has improved by about 15%. This adds up to approximately 35,000 kWh of energy savings per year for each LRV equipped with an ESS. The data used for these findings is very preliminary, as only a few months of running data has been collected, and only includes data from those vehicles equipped with the ESS. Additional data will be compiled which will also include measuring the efficiency of recapturing regenerative braking energy on other vehicles that are not retrofitted with the ESS units. It is anticipated that there will be an improvement, as the ESS is able to recapture excess regenerated braking energy from not only the local vehicle for which it is installed, but also from other vehicles in close proximity. This benefit should add to the overall energy savings created by the on board energy storage units as it will demonstrate the effect the ESS has on the overall fleet.

CONCLUSION

On board energy storage systems can and do improve the efficiency of capturing regenerative braking energy on light rail vehicles. The goal of this pilot project was to become as close to 100% efficient at recapturing excess regenerated braking energy as possible. Though we weren't able to hit the 100% efficiency mark, addition of the DLC based energy storage system did have a significant impact on energy savings. Having an on board energy source also provides some added operational benefits for systems that experience interruptions in overhead power supply or wish to have catenary free sections of track.

Lessons Learned

Though this project has been a success in terms of demonstrating that on board energy storage can improve the efficiency of capturing regenerative braking energy and reducing operational costs, there are areas that leave room for improvement. The system could be more efficient and less intrusive if it is completely integrated with the vehicles propulsion systems. This approach would result in less weight by using one single inverter and line filter instead of two and would allow more efficient control and integration with vehicle propulsion logic. This should reduce the cost of the system which would lead to a quicker return on investment.

More precise control of the charging and discharging algorithms for the ESS would also improve performance. A more intelligent control scheme that was able to sample line voltage conditions and the vehicle's rheostatic braking curves could adjust the ESS charging and discharging curves accordingly which would increase the effectiveness and efficiency of the system.

Recommendations

As technology advances and new devices for storing energy are developed, on board energy storage will still be a valid method for improving the efficiency of energy recovery. Whether double layer capacitors, flywheels, batteries or a new energy storage method are used, the most benefit can be realized if integrated into new vehicle design and exercised on a large scale. Various conditions exist both on the vehicle and on the wayside that contribute to the efficiency of such an auxiliary system. Full integration and intelligent control are key to realizing the most potential for energy savings.