State-of-the-Art in Light Rail Alternative Power Supplies

Prepared for:
APTA / TRB 2015 Light Rail Conference

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ABSTRACT

BACKGROUND

Since the beginning of electrified rail transit in the 1880s, the conventional overhead contact system (OCS) has been the preferred power distribution method for light rail/streetcar/tramway systems (referred to collectively in this paper as “light rail”) throughout the world. Although there have been a number of other approaches tried, all were ultimately found wanting. More recently however, several modern versions of alternative power supply options have entered the marketplace, including onboard energy storage and ground level power supply, allowing operation of vehicles without an OCS (“off-wire”) over part or all of the alignment.

The application of alternative power supplies is a complex subject that is best approached from a systems viewpoint, rather than just the vehicle or the electrification system. In the end, the goal is to provide reliable, continuous traction power to the rail vehicle and there are number of ways this may be done. Followers of this subject will have seen many papers over the years that have identified, described and evaluated many of these methods.

PURPOSE

The purpose of the paper is to examine progress during the last decade in the rapidly changing development of alternative power supply for light rail and to identify major technological advances and trends likely to impact the industry in the coming decade.

METHODS

The authors have conducted an ongoing literature survey, and utilized personal experience, onsite visits and collaborative information exchange with suppliers and users of the technology to develop this paper.

RESULTS

Ten years ago (2005), there were no light rail systems in commercial service using onboard energy storage for off-wire operation, and only one system using ground level power supply (Bordeaux). By the end of 2015 there are expected to be eight cities with ground level power supply systems in commercial service, and nine systems using onboard energy storage for off-wire operation (growing to 13 by the end of 2016).

There are also several more systems of both types under construction. Development of battery, supercapacitor, flywheel and hybrid onboard energy storage systems also continues, as does onboard power generation using hydrogen fuel cells.

CONCLUSIONS

1. Alternative power supply methods for light rail are entering a new phase of development. Compared to ten years ago, there are now a significantly larger number of ‘early adopter’ systems either in commercial service or under construction. While that number is still small compared to the over 400 light rail systems worldwide, interest is strong and the experience gained in operating these systems is expected to facilitate additional improvements and can provide specific information on operating costs, including the life span of energy storage devices, and thus life cycle costs. This will hopefully provide decision makers with additional points to consider and some initial hard data that they currently do not have access to.

2. Proprietary technology issues remain a major factor

3. Application of the technology remains very project specific and may require vehicle performance tradeoffs. Design requires careful analysis of alignment and duty cycle, including local climate factors. There is also a need for more sophisticated tools to properly analyze the various system characteristics and consider a variety of scenarios in order to arrive at a reliable, cost effective off-wire system design

4. Onboard energy storage has multiple uses; it is also used for energy savings by increased recuperation of regenerative braking.

BACKGROUND

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The application of alternative power supplies is a complex subject that is best approached from a systems viewpoint, rather than just the vehicle or the electrification system. In the end, the goal is to provide reliable, continuous traction power to the rail vehicle and there are number of ways this may be done. Followers of this subject will have seen many papers over the years that have identified, described and evaluated many of these methods.

For those who are new to the subject, there are three basic means, as well as emerging hybridized combinations (indicative of how rapidly the technology is evolving):

1. Ground level power supply (GLPS) – power continuously supplied to the vehicle at ground level via direct contact with a conductor or inductively
2. Onboard energy storage system (OESS) – power stored on the vehicle, using flywheels, batteries, supercapacitors or a combination thereof, recharged periodically via regenerative braking and contact with a power conductor
3. Onboard power generation system (OPGS)– power continuously generated on the vehicle as required via hydrogen fuel cells, microturbines or diesel engines

The advantages of these alternative power supply methods center around providing improved aesthetics and the reduction of conflicts with other users of the street space including utilities, bridges, traffic signals and other overhead structures, as well as special events (such as parades), etc.

In the case of OESS, the related infrastructure is also simplified, in some cases reducing short term (capital) and long term (maintenance) infrastructure costs.

The disadvantages include increasing the complexity of the vehicle (OESS) or the wayside infrastructure (GLPS) that may lead to increased capital and/or vehicle life cycle costs. With OESS there are also weight, space and performance tradeoffs, as well as the unknown life expectancy of OESS elements.

Nice, France - short off-wire segments using onboard energy storage. Opened 2007

Only ten years ago (2005), there were no light rail systems in commercial service using OESS for off-wire operation, and only one system using a GLPS (Bordeaux). After a relatively slow start, by the end of 2015 there are expected to be in commercial service:

1. 8 systems using GLPS, with at least 5 more under construction (Table 1)
2. 9 systems using OESS for off-wire operation, with at least 8 more under construction (Table 2)
3. 4 systems using OPGS (diesel hybrid light rail vehicles) for off-wire operation (Table 3)

Significantly, the lengths of the off-wire segments, whether powered by GLPS or OESS, have been slowly increasing, and in a few cases the entire length of a line uses alternative power supply.

Meanwhile, the supporting development of battery, supercapacitor, flywheel and diesel hybrid alternative power systems, as well as onboard power generation using hydrogen fuel cells, has continued on at least 27 prototype / development vehicles (Table 4), with more to come. There are also a number of systems using on-board energy storage primarily for energy saving purposes (Table 5), which as a side benefit, are also in many cases capable of moving a vehicle very short distances off-wire (e.g. out of an intersection).

The following tables provide an overview of the current status (October 2015) of vehicle-borne alternative power supplies for light rail application.

TABLE 1: Ground Level Power Supply Systems (GLPS)

City	Operational	Length, Off Wire	Length, System	Supplier	Technology	Vehicles
Bordeaux, France	2003	13.6 km total segments	44 km, 90 stops, 3 lines	Alstom	APS	79 CITADIS vehicles
Angers, France	2011	1.5 km total segments	12 km, 25 stops	Alstom	APS	17 CITADIS vehicles
Reims, France	2011	2 km segment	12 km, 23 stops	Alstom	APS	18 CITADIS vehicles
Orleans, France	2012	2.1 km segment	12 km, 26 stops, Line B	Alstom	APS	21 CITADIS vehicles
Tours, France	2013	2 km segment	15 km, 29 stops	Alstom	APS	21 CITADIS vehicles
Dubai Al Sufouh, UAE	2014	Completely catenary free	10.6 km, 11 stops	Alstom	APS II	11 CITADIS vehicles, 14 more in 2nd phase
Beijing, China	2015	4 km total segments	9.4 km Xijiao Line	AnsaldoBreda / CNR	Tramwave	31 SIRIO vehicles
Zhuhai, China	2015	Completely catenary free	8.7 km, 14 stops	AnsaldoBreda / CNR	Tramwave	10 SIRIO vehicles
Cuenca, Ecuador	2016	1.2 km segment	10.5 km, 27 stops	Alstom	APS	14 CITADIS vehicles
Rio de Janeiro (Rio Porto Maravilha), Brazil	2016	Completely catenary free	28 km, 24 stops	Alstom	APS plus OESS (supercapacitors)	32 CITADIS vehicles
Lusail, Qatar	2018	22.7 km total segments	33.1 km, 37 stops, 4 lines	Alstom	APS	35 CITADIS vehicles
Sydney, Australia	2019	1.5 km	12 km CBD/ East Line, 13 stations	Alstom	APS	30 CITADIS vehicles
Florence (Firenza), Italy	201?	470 m	7.5 km, 18 stops, Line 2	AnsaldoBreda	Tramwave	SIRIO vehicles

TABLE 2: On-Board Energy Storage Systems for Off-Wire Operation (OESS)

City	Operational	Length, Off Wire	Length, System	Supplier	Technology	Vehicles
Nice, France	2007	0.91 km total segments	8.7 km, 21 stops	Alstom	Battery, (Ni-MH) (SAFT)	20 CITADIS vehicles
Seville, Spain	2011	0.6 km line segment	2.2 km, 5 stops	CAF	ACR Evodrive supercapacitors	4 URBOS 3 vehicles
Shenyang, China	2013	Segments totaling 2.5 km	69.9 km, 65 stops, 4 lines	CNR Changchun	Voith supercapacitors	30 "dolphin" vehicles
Zaragoza, Spain	2013	2 km off-wire segment, charging at stops	12.8 km, 25 stops	CAF	ACR Freedrive battery / supercapacitors	21 URBOS 3 vehicles
Guangzhou, China	2014	Completely catenary free, charging at stops	7.7 km, 10 stops, Haizu Circle Line	CSR ZELC	SIEMENS SITRAS ES supercapacitors (Maxwell)	7 vehicles
Nanjing, China	2014	90% catenary free, OCS only at stops and acceleration points	8 km, 13 stops, Hexi line	CSR Puzhen	Bombardier Primove battery (Li-Ion)	15 FLEXITY 2 vehicles
Kaohsiung, Taiwan	2015	Completely catenary free, charging at stops	8.2 km, 14 stops	CAF	ACR Evodrive supercapacitors	9 URBOS vehicles
Dallas, TX	2015	Oak Cliff Streetcar, 1.6 km	2.6 km, 4 stops	Brookville	ABB battery (Li-Ion nickel manganese cobalt)	2 LIBERTY vehicles
Konya, Turkey	2015	1.8 km	21 km, 35 stops	Skoda	CATFREE battery (nano-lithium-titanium)	12 FORCITY CLASSIC 28T vehicles
Santos, Brazil	2106	0.4 km	11.4 km, 14 stops	Vossloh	ABB battery (Li-titanate)	22 TRAMLINK V4 vehicles
Seattle, WA	2016	Seattle First-Hill Streetcar, 4 km (downhill track)	4 km, 10 stops	Inekon	Battery (Li-Ion)(SAFT)	6 TRIO 12 vehicles
Detroit, MI	2016	New M-1 streetcar line, (length tbd - 60% of system proposed)	5.1 km, 20 stops	Brookville	ABB battery (Li-Ion nickel manganese cobalt)	6 LIBERTY 12 vehicles
Doha Education City, Qatar	2016	Completely catenary free, charging at stops	11.5 km, 25 stops	Siemens	SITRAS HES battery (Ni-MH) / supercapacitors	19 AVENIO vehicles
Granada, Spain	2017	4 segments totaling 4.95 km	15.9 km, 26 stops	CAF	ACR Freedrive battery / supercapacitors	13 URBOS 3 vehicles
Luxembourg	2020	3.6 km off-wire segment between Pont Rouge and Gare Centrale, charging at stops	16 km, 24 stops	CAF	ACR Freedrive battery / supercapacitors	21 URBOS 3 vehicles
Nice	2018	Completely catenary free, charging at stops	11.3 km	Alstom	SRS with Ecopack (battery / supercapacitors)	19 Citadis XO5 vehicles
Munich, Germany	201?	Planned English Garden extension, 1 km with 2 stops	8 km, 4 new stops	Stadler	Battery (Li-ion)	4 VARIOBAHN vehicles with batteries ordered (w/ 10 more pre-wired for future battery retrofit) All delivered, but only one vehicle currently fitted with batteries pending construction of new line.

Zaragoza, Spain- 2 km off-wire segment using onboard energy storage, opened 2013

TABLE 3: Diesel Hybrid (Tram Train) Vehicles for Off Wire Operation (OPGS)

City	Operational	Length, Off Wire	Length, System	Supplier	Technology	Vehicles
Nordhausen, Germany	2004	8 km	9 km, 5 stops, Line 10	Siemens	Diesel hybrid	3 COMBINO DUO tram train vehicles
Kassel, Germany	2006	28 km	30 km, 27 stops, Line RT4	Alstom	Diesel hybrid	10 REGIOCITADIS tram train vehicles
Leon, Spain	2011	New FEVE tram train route Leon - Cistiernia	24 km	Vossloh	Diesel hybrid	4 TRAMLINK tram train vehicles
Chemnitz, Germany	2014	Three new tram train lines to Burgstädt, Mittweida and Hainichen		Vossloh	Diesel hybrid	8 CITYLINK tram train vehicles

TABLE 4: Development Prototypes

Installer	Operational	Location	Supplier	Technology	Vehicles
Alstom	1999	LaRochelle, France, Alstom Test Track	Alstom	Magnet Motor flywheel	CITADIS vehicle, STARS program . First use of charging at station stops
Alstom	2001	Karlsruhe, Germany Line 1	Duewag	Turbomeca microturbine hybrid with CCM EMAFER flywheel energy storage	Ex - VBK GT8 vehicle, ULEV-TAP (Ultra Low Emission Vehicle - Transport using Advanced Propulsion) program.
Spie-Enertrans	2001	Marseille, France Line 68	La Brugeoise	Innorail ground contact system	RTM PCC vehicle
Alstom	2002	LaRochelle, France, Alstom Test Track	Alstom	Innorail / APS ground contact system	CITADIS vehicle
Bombardier	2003-2007	Mannheim, Germany	Bombardier	MITRAC Energy Saver supercapacitors	DUWAG GTN6 vehicle
Siemens	2003-2005	Karlsruhe, Germany	Siemens	Diesel hybrid with 2 CCM flywheel energy storage units	AVANTO / S70 vehicle, ULEV-TAP 2 program.
Alstom	2006-2008	Rotterdam, Netherlands	Alstom	CCM flywheel	CITADIS vehicle, ULEV program
Kawasaki	2007-2008	Sapporo, Japan	Kawasaki	Gigacell battery (Ni-MH)	SWIMO-X demonstrator vehicle, RTRI sponsorship
Siemens	2007	Lisbon (Almada), Portugal	Siemens	SITRAS HES (energy saver) battery / supercap.	COMBINO PLUS vehicle
Tokyu Car	2007-2008	Sapporo, Japan	Tokyu Car	Battery (Li-Ion)	HI-TRAM demonstrator vehicle, RTRI sponsorship
Alstom	2009-2010	Paris, France	Alstom	ECOPAK Supercapacitors	CITADIS vehicle, STEEM program
AnsaldoBreda	2010	Naples, Italy, 0.4 km test track and 0.6 km Poggioreale-Via Stadera line	AnsaldoBreda	Tramwave ground contact system (2nd generation STREAM)	SIRIO vehicle
Stadler	2011	Velten, Germany test track	Stadler	Battery (Li-Ion)	VARIOBAHN vehicle from MVG Munich order. One of four to be used on a future catenary free line through English Garden.
Bombardier	2011-2012	Augsburg, Germany, 0.8 km Primove test track	Bombardier	Primove (inductive) current collector / battery	VARIOBAHN test vehicle
Fenit Rail	2011	Valencia, Spain	Fenit Rail	Fuel cell (hydrogen) / battery (Li-ion) / supercapacitors	Ex-SNCV FABIOLOS 3400 series vehicle, supported by local government funds.
KinkiSharyo	2011	Various US cities	KinkiSharyo	Battery (Li-Ion)	AMERITRAM demonstrator vehicle,
AnsaldoBreda	2012	Florence (Firenza), Italy	AnsaldoBreda	Supercapacitors	SIRIO vehicle
AnsaldoBreda	2012	Bergamo, Italy	AnsaldoBreda	Supercapacitors	SIRIO vehicle
Hyundai Rotem / KRRI / KAIST	2007-2014	Gyeonggi-do,Korea	Hyundai Rotem	Battery (Li-Ion) / OLEV power transfer system	WTRAM prototype vehicle' Korea Railroad Research Institute. OLEV system Korea Advanced Institute of Science & Technology.
Vossloh	2013	Valencia, Spain	Vossloh	Battery (Li-Ion)	TRAMLINK vehicle
Siemens	2014	San Diego, CA	Siemens	Battery (Li-Ion)	S70 vehicle, World record distance off wire (24.6 km)
CSR	2014	CSR China	CSR	Supercapacitors	4 module prototype vehicle
CAF	2015	Vitoria-Gasteiz, Spain	CAF	Battery (Li-Ion)	URBOS 2 vehicle, OSIRIS project
Bom Sinal (Vossloh VLT licensee)	2015	Brazil	Bom Sinal	Battery	TRAMLINK VLT based vehicle, CPDM-VE project.
CSR Sifang (Skoda licensee)	2015	Quingdao, China	CSR Sifang Quingdao	BALLARD FCvelocity fuel cell (hydrogen)	ASTRA 15T vehicle
Pesa	2015	Krakow, Poland	Pesa	Supercapacitors	SOLARIS TRAMINO vehicle
Toshiba	2015	Kagoshima, Japan	Alna Sharyo	Toshiba SCiB compact battery (Li-ion)	LITTLE DANCER Type A3 vehicle.

TABLE 5: On Board Energy Storage for Energy Savings

In addition to numerous prototype vehicles used for evaluating onboard energy storage systems for energy savings (reference Table 4), the following light rail vehicles are known to have been fitted with such systems for commercial use. This list is not comprehensive and further research will be required to compile a more complete list.

City	Year operational	Area of Operation	Supplier	Technology	Vehicles
Portland, Oregon	2012	TriMet system	American Maglev	Supercapacitors (Maxwell)	27 SD660 vehicles retrofitted under TIGGER III grant
Rhine-Neckar, Germany	2012	Mannheim to Heidelberg Line	Stadler	Bombardier MITRAC Energy Saver supercapacitors	30 VARIOBAHN vehicles
Rostock, Germany	2014		Vossloh	Vossloh Kiepe supercapacitors	13 TRAMLINK 6N2 vehicles
Seattle, WA	2014	Sound Transit LINK LRT System	KinkiSharyo	Supercapacitors	3 existing 1500 VDC KinkiSharyo LRVs retrofitted under TIGGER grant
Cuiaba, Brazil	2015		CAF	ACR Evodrive supercapacitors	40 URBOS 3 vehicles
Wrockclaw, Poland	2015		Pesa	Supercapacitors	6 TWIST vehicles

Dallas, Texas - 1.6 km off-wire segment using onboard energy storage. Opened 2015

The last five years has seen increasing interest in unconventional means of propulsion throughout the transportation sector. For road transport vehicles, electric drives have become more and more commonplace. The battery, supercapacitor, flywheel and fuel cell technology needed to power these electric drives has advanced considerably, with more efficient, smaller, lighter and cost effective designs becoming commercially available, along with increasing modularity, a trend that is expected to continue.

Although the automotive sector is clearly driving development of onboard power sources, it is interesting to note that of all the vehicles used to transport people today, the modern light rail vehicle has for some while been perhaps the best candidate for their use, as they were already electrically propelled and have had the ability to regenerate braking energy as a standard feature. Market factors, such as low production quantities, cost, space requirements, weight and complexity, as well as the inherent conservatism of the rail vehicle marketplace where vehicles and their systems are typically expected to last 30 or more years, have initially slowed progress in this direction, but that is now changing.

The use of energy storage (both wayside and onboard) to achieve energy savings continues to grow, particularly in Europe where higher energy costs provide increased incentive. As a result, numerous projects have reported out their analyses for calculating return on investment (e.g. calculating payback period). As a result of these studies, significant discussion on the subject of new vs. retrofit of alternative power supplies has also emerged. Feedback from the carbuilders, combined with numerous studies, indicate that it is far more efficient to design in energy storage equipment from the beginning than to retrofit it. Fewer components and cleaner interfaces, less weight, standardized elements, all combine to reduce cost and thus shorten the return on investment period.

The following sections review the most significant advances for the three primary types of alternative power supply technologies for light rail applications.

GROUND LEVEL POWER SUPPLY (GLPS)

Background

The modern quest for “wire free” zones for light rail systems began in 1999 when the ancient city of Bordeaux, France wanted to build a new system that traversed an historically important area containing their 13th century cathedral and crossed an historic bridge over the Garonne without the use of overhead wires. It was not until 2003 that the first 3 km GLPS segments of the system opened, but today more than 31 km are in commercial service worldwide, with more on the way.

This initial approach to providing off-wire capability concentrated on providing continuous ground level power to the vehicle, either via a switched direct contact system, such as APS or TramWave or an inductive power transfer system such as Primove or OLEV Power Track. The continuous power supply approach is particularly advantageous in extreme climates where heavy duty heating and air conditioning is required, and for alignment sections with steep up-hill gradients where on-board energy storage systems are quickly drained. As seen in Table 1, the APS system is the most mature, having been through many teething problems to become very reliable and is now the market leader for ground level power supply. Other ground level systems are generally less well proven, but they are also now beginning to attract buyers. The suitability of GLPS in climates with heavy snowfall (and the attendant use of plows and road salt for snow removal) also remains an open question.

Issues

In all GLPS installations to date, a single supplier has provided both the vehicles and the power distribution infrastructure. While this system-level approach is logical, the proprietary nature raises commercial issues that represent one of the biggest hurdles to the wider adoption of such systems. In the US, sole source procurements of this nature are difficult to support under FTA procurement guidelines and longer term, it locks an agency into a single technology and a single vehicle type from a single supplier, which carries some level of uncertainty regarding future support and further development.

There are indications that some suppliers are willing to supply the GLPS system separate from the vehicle, but there have been no applications of this approach to date and the power transfer system itself still remains a proprietary, sole source system.

The closely related issue of costs for GLPS has also been a significant factor. The initial APS system installation was said to be 8 times as expensive as traditional OCS. Even though that price reflected significant engineering and development costs for the relatively short length of APS equipped track (3 km), no specific pricing data is available today, and so it seems clear that GLPS remains an expensive solution. In the opinion of the authors, it is perhaps possible that GLPS systems are best suited to supply as part of "turnkey" packages that offer the supplier the ability to provide vehicles and infrastructure as a package together with long term maintenance.

This approach could help optimize risk sharing and spread the costs over a wider scope of supply, preserving necessary margins for the supplier while still offering the customer value for money.

Advances

The high costs of the complex underground infrastructure associated with GLPS has led suppliers to propose various non-continuous solutions in the last few years. Although continuous GLPS systems already utilize an onboard battery for limited use in working around segment outages, adding a more robust onboard energy package provides two significant advantages; chiefly the potential to simplify the infrastructure by limiting the use of the expensive ground power supply system components to locations where it is convenient for charging (e.g. at stops), or needed for demanding power use (e.g. accelerating zone out of stops, hills, etc.), thus making the system more affordable. And in the case of APS, this would also offer the potential to utilize regenerative energy from braking, which is not possible with the current generation of this technology. An example of this migration is found in the new tramway system currently under build in Rio de Janeiro, which will utilize supercapacitor-based energy storage on the vehicles in combination with Alstom APS ground level supply. An Alstom press release states that the system is completely catenary free, but the APS ground power supply will only be installed over 80% of the system.

ONBOARD ENERGY STORAGE (OESS)

Background

As the first GLPS system was going into service in 2003, efforts were also being made to provide vehicle power by use of OESS based on battery, supercapacitor and flywheel technology. Initial experiments focused on achieving energy savings through increased recuperation of regenerated braking energy, with off-wire operation a natural outgrowth. Nice, France was the first city to introduce commercial off-wire operation using OESS, debuting in 2007 with two short segments.

Issues

From an operational perspective, the most significant trade-offs of the OESS approach to off-wire center around the fact that it is not a continuous form of power supply. The energy storage units need to be periodically recharged, and vehicle performance restrictions are typically implemented as part of optimizing the amount of energy storage to be carried on the vehicle. One example is "load shedding" which is relatively straight-forward from a technical perspective, although its impact on operations is less clear. A good example would be reducing air conditioning in a scenario where a vehicle has become stuck in traffic- advantageous from an energy conservation point of view, but perhaps unacceptable from a customer service perspective in hot climates. In the end, careful design is required to find the optimal balance between energy storage capacity and the associated weight and space requirements. The additional equipment required to integrate the OESS also adds a further degree of technical complexity to the vehicle.

How charging is achieved also depends on the system design – if only short off-wire segments are to be traversed, then charging via the OCS is often a workable approach. However if it is desired to have an extended off-wire section, or even a completely "catenary free" system, then it is necessary to recharge by other means, usually at station stops via either a conventional pantograph and an overhead conductor, or via a ground level pick-up or inductive charging system. This overhead "charging station" approach using modified pantographs has now been applied to new systems in Guangzhou, Kaohsiung, Nanjing and Doha Education City.

This has the advantage of being very straightforward and non-proprietary. Reliability can be improved by incorporating an automatic location system to raise and lower the pantograph in the right places.

Another operational issue has to do with the inherent hazards associated with onboard energy storage. Maintenance practices will be impacted by the presence on the vehicle of what in many cases is effectively a constantly charged power source. Additionally, the prevailing use of Li-Ion type batteries requires a significantly different level of care than battery technologies such as lead acid or NiCad commonly used on many types of rail vehicles.

From a cost perspective, the most significant trade-off inherent in the OESS approach is the initial impact on vehicle capital costs and the life cycle cost of periodic replacement of the onboard energy storage units. Although detailed, unbiased cost information is generally not available (in common with other forms of alternative power supply) it is clear that the system operator will need to make significant allowances for ongoing renewals throughout the life of the vehicle, although as the technology improves, the time between upgrades may continue to increase, and the costs reduce.

Advances

Advances in the area of OESS center around the continuing evolution of the energy storage units themselves. Of these, batteries (usually lithium-ion) and supercapacitors (or a combination of the two) have enjoyed the greatest success so far, but continuing development of high tech flywheel technology (such as the GKN / Williams Hybrid Power MLC flywheel units) may well see their widespread use. An added advantage to all of these technologies is that they are supported by the world automotive market, where there is considerable research and development. Further, with careful design, it is also possible to utilize OESS to achieve energy savings through improved capture of regenerative braking energy, offering the potential for new systems to realize a reduction in the number of substations, or for an existing system to add service or transition to a modern fleet with limited upgrading of the power network.

OESS systems with periodic charging are currently one of the most promising and widely available approaches available for those seeking an end to overhead wires. It will be interesting to see how the inherent trade-offs are dealt with once the new crop of systems becomes fully operational, particularly in cities with extreme climates where power demand from vehicle HVAC systems is significant.

ONBOARD POWER GENERATION (OPGS)

Background/Issues

The OPGS approach to alternative power supply has been the slowest to develop, seeing more modest commercial application than GLPS and OESS. Advances have however been made in various approaches to fueled power generators on the vehicle. The trade-offs involve impacts on vehicle weight and configuration due to the related space impacts arising from both the power generator and the associated fuel storage / refueling facilities required.

In 2004, a small fleet of trams in Nordhausen Germany was locally fitted with a motor-generator package based on automotive diesel engines. Other European suppliers have followed a similar approach for light rail vehicles that needed to operate on both existing electrified lines within the city center and travel out to neighboring cities on existing regional rail lines without the expense of electrifying the entire line. Known in Europe as “tram-trains”, these vehicles are most commonly straight electric with dual voltage capabilities, but the diesel hybrid type has now also carved out a niche for itself, although it remains a limited market.

Advances

The most significant progress relating to onboard power generation involves the hydrogen fuel cell. It has been predicted that 2015 will be the year of the fuel cell and that appears to be true. Toyota has announced the first production series fuel cell cars will be built this year and at least two fuel cell development light rail vehicles are under evaluation. Alstom has selected Hydrogenics to provide fuel cells for regional trains, while the CSR LRV and other rail vehicle demonstrators use Ballard and no doubt other light rail versions are under development. Costs are still high for the fuel cell units and hydrogen supplies are not yet widely available, but this technology looks to be the wave of the future.

As noted earlier, the application of alternative power supplies to any light rail system requires a detailed system-specific approach and full consideration of all the variables involved in order to select the right technology and to optimize the size of the energy storage elements involved to provide the most cost effective solution. This is far from being a simple task – as a minimum, the following variables will affect the analysis and design process for both GLPS and OESS systems:

Duty Cycle
- Operating headways (initial and future)
- Operating consists (single car, multiple cars)(initial and future)
- Distance between stops (off wire)
- Dwell times at stops (off wire)
- Dwell time at turnarounds (under OCS)
- Operating time / distances under OCS

Alignment
- Alignment curvature and gradients (off wire)
- Track arrangement (single track, double track, passing loop, crossing, junction, etc.)(off wire)
- Level of priority at traffic lights (none, predictive, priority)
- Number of road crossings between station stops (off-wire)
- Degree of operation shared with road vehicles
- Local speed limits
- Availability of space for wayside sub-stations, power feeders, etc.
- Future system expansions (including any off-wire sections)

Operating Environment
- Temperature dependent vehicle loads (heating and air conditioning)
- Local climactic conditions (ice, snow, extreme heat)
- System regeneration limitations (line receptivity, regen initiation voltage, maximum regen voltage)
- Energy costs and contractual arrangements (including peak demand charges, etc.)

Vehicle Systems
- Space available on board vehicles
- Capacity, recharge time, size, weight and cost of energy storage elements
- Capacity, size, weight, efficiency and cost of dc to dc inverter and ancillary equipment (power pick-up elements, vehicle GPS / controls, etc.)
- Cooling, monitoring, charge / discharge control, maintenance approach for energy storage elements
- Fire detection / prevention / containment considerations for energy storage elements
- Life expectancy of energy storage elements
- Replacement, disposal / recycling of energy storage elements

Similar operational, alignment and climactic requirements also apply to OPGS, as well as:
- Capacity, size, weight and cost of onboard power generation elements
- Capacity, size, weight and cost of fuel storage elements
- Cost and availability of selected fuel
- Refueling periodicity / refill time
- Wayside refueling equipment requirements
- Cooling, exhaust, monitoring, control, maintenance approach
- Fire detection / prevention / containment considerations
- Noise / vibration mitigation

Given all these variables, there is a need for more advanced simulation tools that will allow the designer to input and adjust the various parameters to obtain an optimal solution.

Doha, Qatar - 11.5 km catenary-free line, using onboard energy storage with recharging at each station. Opening 2016

CONCLUSIONS

Alternative power supply methods for light rail are entering a new phase of development, offering system designers an important new tool in the toolbox. Compared to ten years ago, there are now a significantly larger number of 'early adopter' systems either in commercial service or under construction. While that number is still small compared to the over 400 light rail systems worldwide, interest is strong and the experience gained in operating these systems is expected to facilitate further improvements and to start helping to answer the significant questions concerning life cycle costs. In parallel with the evolution of alternative power systems for light rail vehicles, there is automobiles and other forms of road transport (including electric transit buses) are seeing.

Issues impacting the application and development of alternative power supply to light rail include:

1. From a commercial perspective, proprietary technology issues remain a significant point, particularly for ground power systems which involve significant equipment on the wayside. Ultimately, buyers want a mature (service proven) technology that conforms to agreed industry standards, allowing designers to select from a range of competing suppliers. At this time the relatively new field of alternative power supply is not in this position; it has limited standards and a series of competing, highly customized designs.

   Decision makers have relatively little hard data on capital and life cycle costs for GLPS and OESS. Given the relative newness of the technology, the small quantities involved, and the competing proprietary designs, it may not be practical to expect that detailed, unbiased cost data will be available anytime soon. Instead, it may be necessary to consider technologies such as GLPS only within a project delivery framework that allows a single supplier to provide the vehicles, related infrastructure and long-term maintenance as part of a turnkey package, thus providing an opportunity to better allocate risks associated with capital and life cycle costs.

   There will, however, be an increasing number of projects in operation in the next decade, so it is possible that additional data can be obtained and analyzed.

   Together with standards covering key related topics (e.g. safety measures for use of Li-Ion batteries on light rail vehicles), both the suppliers and the buyer will be in a better position to continue developing alternative power supplies for light rail.

2. From a project design perspective, application of alternative power supply technologies remains very project specific and may require vehicle performance tradeoffs, particularly with OESS. Its design is an iterative process that requires careful analysis of alignment and duty cycle, including local climate factors in order to balance the amount of energy storage capacity with the associated weight, space and performance tradeoffs. Given the significant impacts on multiple aspects of project design, balancing the need for an early commitment to off-wire operation (e.g. in the environmental phase) with traditional project design approaches may be challenging.

   There is also a need for more sophisticated tools to properly analyze the various system characteristics and consider a variety of scenarios in order to arrive at a reliable, cost effective off-wire system design.

3. Onboard energy storage has multiple uses; its application began with a desire for energy savings by increased recuperation of regenerative braking energy, and has expanded into the ability to provide off-wire operation.

4. Although hydrogen fuel cell powered vehicles hold great promise for the future, currently the most economical and straightforward approach to off-wire operation is onboard energy storage with periodic recharging. Recharging can be at station stops, or combined with recharging under wired sections of the alignment. To operate such as system reliably, it seems likely that automating the recharging process, rather than relying on manual human actions will be required.

5. From a project planning perspective, the implications of including a commitment to off-wire operation in a project's environmental documentation, and then later altering the approach based on further refinement of project costs and objectives, remains unclear.

1. What industry R&D process changes could further speed up / improve development? What tools are needed to more efficiently analyze requirements?

2. New vs. retrofit- what are the economics of buying a light rail vehicle as "off wire capable", meaning effective steps to facilitate the future addition of this capability? Besides reserving physical space, what other design elements need to be considered?

3. Related to the above question, what new standards, or changes to existing standards, may be needed to facilitate application of these technologies and to ultimately lessen the impacts of proprietary technology?

4. Design issues associated with frequent charging (e.g. at stops). These may include having to raise and lower the power transfer element – having the operator do this leaves a high likelihood of human error, while an automated system adds complexity and cost, but increases system reliability. For systems with a mixture of conventional OCS and off-wire operation, are their conflicting requirements related to pantograph design? Other related design issues include power distribution for "charging stations", centering around the trade-offs between centralized substations feeding the charging points, versus localized power conversion equipment at each point.

Kaohsiung, Taiwan - 8.2 km catenary-free line, using onboard energy storage with recharging at each station

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