# Appendix 6

## Electrification Systems Technology Assessment

December 2010

**METROLINX**
An agency of the Government of Ontario

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# APPENDIX 6

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December 2010

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# EXECUTIVE SUMMARY

## Context

Metrolinx operates a comprehensive transportation system of light rail transit, bus and commuter rail lines in the Greater Toronto and Hamilton Area (GTHA). The system includes the GO rail network which is an essential part of Metrolinx's service to the area commuters. GO Transit currently provides commuter rail service on seven corridors in the GTHA, using conventional diesel-electric locomotives and non-powered bi-level coaches in push-pull configuration.

In late 2008, Metrolinx published a Regional Transportation Plan – The Big Move – a multimodal vision for regional transportation to strengthen the economic, social and environmental sustainability of the Greater Toronto and Hamilton Area. The Big Move sets out a fast, frequent and expanded regional rapid transit network as a key element of the plan. The plan includes establishing Express Rail and Regional Rail services at speeds and frequencies that could be enhanced by system electrification.

Metrolinx, has been asked by the Ontario government to build, own and operate the Air Rail Link (ARL) from Union Station to Pearson Airport. The ARL will provide a premium express rail shuttle service between Union Station and Pearson Airport.

## Electrification Study

Metrolinx has initiated a study of the electrification of the entire GO rail system as a future alternative to diesel trains now in service. The electrification study is examining how the future GO rail services and the Airport Rail Link will be powered – using electricity, enhanced diesel technology or other means – when these services are implemented in the future. The study assesses the advantages and disadvantages of a full range of technology options, including ac and dc powered systems and alternative system technologies and enhancements. The study reflects the existing GO Transit network, the proposed network expansions to St. Catharines, Kitchener/Waterloo, Allandale, Bloomington, Bowmanville, as well as the future Pearson Air Rail Link.

## Electrification Technology Assessment

The objective of this report is to identify and assess a broad range of existing and future potential electrification system technologies that could be used to provide power to the future GO rail services. The electrification system technologies considered include the following candidates:

- DC Electrification Systems
- AC Electrification Systems at Commercial Frequency
- AC Electrification Systems at Non-Commercial Frequency
- Combination of AC and DC Electrification Systems
- Alternative System Technologies and Enhancements, Including:
- Wayside Energy Storage

- Wayside Hydrogen Fuel Cell Power Generation

In addition to describing and comparing the technical attributes of these technologies, the electrification system technology assessment involved the use of five screening criteria to identify a "short list" of technologies for further assessment. The criteria used in the assessment include:

- Is the technology **proven**?
- Is the technology **technically viable**?
- Is the technology **commercially viable**?
- Is the technology **compatible with the Reference Case[1] infrastructure?**
- Is the technology **compatible with the Reference Case service levels**?

## Short List of Technologies

Following examination of the candidate electrification system technologies, a number of technology alternatives were eliminated from further consideration based on the application of the screening criteria. Further, it was determined that the following technologies satisfy the evaluation criteria to the highest degree, and therefore should be carried forward for more detailed assessment and analysis as part of the electrification study:

- Direct-fed system operating at 1x25 kV ac electrification voltage and commercial frequency of 60 Hz
- Autotransformer-fed system operating at 2x25 kV ac electrification voltage and commercial frequency of 60 Hz
- Direct-fed system operating at 1x50 kV ac electrification voltage and commercial frequency of 60 Hz

## Technology Recommendation

Hydro One indicated a preference for connections to its 230 kV network in the central Toronto area. The 230 kV transmission lines in close proximity to the rail network that have sufficient supply capacity are located near Horner Ave and Kipling Ave, approximately 14 km west of Union Station and near St. Clair Ave East and Warden Ave, approximately 14 km east of Union Station.

During further evaluation it also became apparent that some bridges along the route have limited vertical clearance. Since the 1x50 kV electrification system requires higher vertical clearance above the

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[1] The "Reference Case" describes existing attributes and planned enhancements of GO's rolling stock, rail infrastructure and services levels – as a basis for identifying and comparing rolling stock and electrification system technologies that could be used for future services.

rail than the 2x25 kV system, more bridges would have to be modified should the 50 kV system be implemented. This would be uneconomical due to requirements for frequent track lowering or bridge raising.

Therefore, the technology selected and recommended for development of conceptual design and cost estimate of the GO system electrification is:

- Autotransformer-fed system operating at 2x25 kV ac electrification voltage and commercial frequency of 60 Hz

The advantage of the 2x25 kV autotransformer-fed system is that it achieves substation “reach” comparable to the 50 kV system with the need to provide clearances only for 25 kV voltage. The system is being used extensively overseas and in the US the system is used by Amtrak on the Northend Electrification system from New Haven, CT to Boston, MA, a distance of 156 miles. The autotransformer system is a standard system used for the type and size of commuter networks like the GO network. Other examples of commuter railroads in US being powered by the same system in revenue service include:

- New Haven Line from Pelham, NY to New Haven, CT operating at 2x12.5 kV, 60 Hz, and owned by Metro-North Railroad (MNR)
- Morris & Essex Line from Kearny Junction in Kearny, NJ (just outside New York, NY) to Dover, NJ and Gladstone, NJ operating at 2x25 kV, 60 Hz, and owned by New Jersey Transit (NJT)
- Commuter line network in Philadelphia and its suburbs operating at unique 24 kV/12 kV, 25 Hz, and owned by Southeastern Pennsylvania Transportation Authority (SEPTA)

The 2x25 kV autotransformer-fed system is also being employed in the design for electrification of the Caltrain commuter route from San Francisco to San Jose.

In Canada, the Agence Métropolitaine de Transport (AMT) uses direct-fed 1x25 kV, 60 Hz system for electrification of their Deux Montagnes commuter line, however, the 2x25 kV, 60 Hz autotransformer system is being considered in AMT’s electrification study.

## Next Step

Following the selection of the electrification technology, conceptual system design and cost estimate for Metrolinx GO system electrification will be developed. This effort, described in a separate report, currently being prepared, includes train operation simulation, traction power system modeling, conceptual electrification system design, and capital, operation, and maintenance cost estimates for the proposed GO network electrification.

# 1. INTRODUCTION

## 1.1. Purpose and Objective of The Study

Metrolinx is considering electrification of its GO transit system. All GO system corridors originate at Toronto Union Station and radiate out to the west, east, and north of Toronto. Including the planned expansions to St. Catharines, Kitchener/Waterloo, Allandale, Bloomington, Bowmanville, as well as the future Pearson Air Rail Link, the system is planned to expand to an ultimate network of 317 route-miles or 510 route-kilometres.

The objective of this report is to identify a broad range of existing and future potential electrification system technologies. Following the establishment of technical criteria that influence the technology choices, the system options are reviewed and compared. Based on this evaluation, technologies clearly not suitable for GO network electrification are removed from the Electrification Study and eliminated from further consideration. The technologies suitable for application to the GO commuter rail corridors are retained and advanced in the Electrification Study for further evaluations.

The study includes the following:

- Overview of rail system electrification technologies in use around the world
- Assessment and evaluation of the electrification technologies and identification of short list of technologies suitable for GO system electrification
- Identification of the preferred technology for Metrolinx GO system electrification

With the suitable technologies identified, a comprehensive computer-aided train operation simulation and electrical system load-flow study will be performed. The load-flow study, described in a companion report, will take into account all relevant rolling stock performance characteristics, track alignment infrastructure data, electrification system parameters and train operation data. The results of the operation and the load-flow simulations will provide the necessary data for development of a conceptual design and cost estimates.

### *Technologies Considered*

The electrification system power supply and distribution system options considered in the Electrification Study and presented in this report, include the following technologies:

- DC Electrification Systems
- AC Electrification Systems at Commercial Frequency
- AC Electrification Systems at Non-Commercial Frequency
- Combination of AC and DC Electrification Systems
- Alternative System Technologies and Enhancements, Including:
- Wayside Energy Storage
- Wayside Hydrogen Fuel Cell Power Generation

Document Definitions and Glossary of Terms are presented in Appendix A.

### *Scope of The Study*

The study will consider the following corridors for electrification as shown in Table 1-1.

***Table 1-1 - Rail Corridors Considered for Electrification***

| Line | From | Via | To | Approximate Distance | |
|---|---|---|---|---|---|
| | | | | (miles) | (km) |
| Lakeshore West | Toronto, Union Station | Hamilton Junction | Hamilton TH&B[2] | 39.9 | 64.2 |
| | | | St. Catharines | 71.2 | 114.6 |
| Lakeshore East | | Pickering | Bowmanville | 42.9 | 69.0 |
| Milton | | Meadowvale | Milton | 31.2 | 50.2 |
| Georgetown | | Georgetown | Kitchener | 62.6 | 100.7 |
| Barrie | | Barrie South | Allandale | 63.0 | 101.4 |
| Richmond Hill | | Richmond Hill | Bloomington | 28.5 | 45.9 |
| Stouffville | | Kennedy | Lincolnville | 31.1 | 50.0 |
| Pearson Air Rail Link (ARL) | | Weston | Lester B. Pearson Airport | 15.4 | 24.8 |

The Table shows the lengths of each individual route of its own, meaning that, segments shared by two or more lines are reflected in each line. For example, both Lakeshore West lines, to Hamilton TH&B and

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[2] Toronto, Hamilton and Buffalo

to St. Catharines, include the length of the Union Station to Hamilton Junction segment. The table includes the existing GO network, and the proposed network expansions to St. Catharines, Kitchener, Allandale, Bloomington, Bowmanville, as well as the future Pearson Air Rail Link.

### *Sources of Study Data*

Numerous photographs are presented throughout the report to illustrate the various technology options and electrification systems in service today. Some photographs were taken by LTK employees and some are public domain from Wikipedia, The Free Encyclopaedia.

### *Study Presentation*

This report is presented in a single volume containing the main body of the report and Appendices. Further information on the electrification technologies can be found in the following companion reports:

**Rolling Stock Technology Assessment for Metrolinx GO System Electrification.** The report evaluates a number of rolling stock technologies and concludes that the most suitable technologies for Metrolinx GO system electrification are the electric locomotive hauled trains, the electric multiple unit (EMU) trains, and the dual-mode locomotive hauled trains.

**Conceptual System Design and Cost Estimate for Metrolinx GO System Electrification.** The report, currently being prepared, includes train operation simulation, traction power system modeling, conceptual electrification system design, and capital, operation, and maintenance cost estimates for the proposed GO network electrification.

# 2. ELECTRIFICATION TECHNOLOGY OVERVIEW

## 2.1. Basic System Definitions

A conventional Traction Electrification System (TES) provides electrical power to the trains by means of the traction power supply system, traction power distribution system, and traction power return system. In general, two types of electrification systems are available, dc-powered and ac-powered systems.

The fundamental difference between the dc-powered and ac-powered systems is that, in dc systems, each substation includes transformers and rectifiers which condition the power to relatively low voltage suitable for direct use by the vehicle propulsion equipment. In ac-powered systems the power is supplied by the substations directly, without rectification, at relatively high voltage necessitating further transformation on-board of the rolling stock for the voltage to be suitable for use by the vehicle propulsion equipment.

Since the on-board transformer imposes a significant weight onto the ac rolling stock, the dc systems are more suited for urban transportation with relatively short passenger station spacing where frequent and high acceleration starts are required. The ac systems are more suited to commuter and intercity systems where the passenger station spacing is relatively long and higher speed between the passenger stations is more important.

Each system type, whether dc or ac, is comprised of the following:

- Traction Power Supply System - includes traction power substations located along the route at predetermined locations.
- Traction Power Distribution System - consists of the overhead contact system (OCS) or third rail system. Additionally, switching stations are required for ac direct-fed systems and along track feeder system, autotransformer stations and switching stations are required for autotransformer-fed system.
- Traction Power Return System - comprised of the running rails, impedance bonds, and cross-bonds. In addition, ac electrification systems also use the ground (earth) itself as a part of the return system and are also equipped with static wires and grounding connections.

The traction power supply system delivers power to the distribution system. The trains collect their propulsion power from the distribution system by means of pantographs or third rail current collector shoes, and return the power to the substations via their wheels by the traction power return system.

### *DC Electrification Systems*

Modern dc electrification systems can be energized at 750 V dc, 1,500 V dc, and 3,000 V dc electrification voltages. For the same power requirement, the higher the voltage, the lower the catenary currents. At higher voltages the traction power substations can be located at wider intervals along the alignment which results in a more economic installation. Substation spacing in any electrification system will depend on train power demand, train operating headways, system design, and real estate availability. However, typical substation spacing is approximately 1.5-2 km for 750 V dc systems, approximately 3-4 km for 1,500 V dc systems, and 6-8 km for 3,000 V dc systems.

The substations receive power from the utility system at medium voltage, 13.8 kV, 24.9 kV or 34.5 kV. Each substation includes one or more transformers, each feeding its own rectifier. The rectifier output is connected between the overhead catenary system, or third rail, and the running rails. In typical dc systems, the substations are rated in the 1 MVA to 6 MVA range, depending on the electrification voltage and train loading.

With Metrolinx operating 10 car- trains, the catenary currents would be too high at the low dc system electrification voltages. For example, a single 10-car EMU train can draw, during acceleration, in excess of 12,000 A at 750 V dc, 6,000 A at 1,500 V dc, and 3,000 A at 3,000 V dc electrification voltages. Such current demands are too high for a conventional catenary system to supply due to potential thermal damage to OCS conductors.

DC electrification using third rail at 750 V dc would be technically feasible, however the major concerns include safety at grade crossings, a practical top speed limit of 130 km/h, requirement for substantial land taking due to large number of substations, and the corresponding power utility interfaces required for substation spaced at relatively short distances of approximately 1.5-2 km.

Therefore, the dc electrification systems alone are not considered as suitable for Metrolinx electrification, and are removed from further consideration in the Electrification Study. Additional evaluation of dc electrification in combination with an ac electrification system is discussed later in this Section.

### *AC Electrification Systems Operating at Commercial Frequency*

#### *General*

AC electrification systems operating at commercial frequency of 60 Hz (50 Hz in Europe and most of Asia), receive their power directly from the local power utility system without the need for frequency conversion[3]. The ac electrification systems can be designed and built in the following basic configurations:

- Direct-fed System
- Autotransformer-Fed System
- Booster-Transformer System

The direct-fed system is the simplest system. At traction power substations electrical power is taken from the utility circuits, transformed to rolling stock utilization voltage, and supplied to the overhead catenary system. In the autotransformer-fed system, the utility power is transformed to higher voltage than the rolling stock can utilize. This higher voltage is then supplied to the overhead catenary and feeder systems and is stepped-down to the vehicle utilization voltage along the route by autotransformers. The booster-transformer system is a variation on the direct-fed system that results in reduced electromagnetic interference (EMI). Although not used recently, it is mentioned in this report

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[3] Systems operating at non-commercial frequency and requiring frequency conversion are discussed later in this report.

for completeness. The characteristics of each system and their advantages and disadvantages are discussed below.

### *Direct-Fed System*

Direct-Fed Systems (DF) operate at 12.5 kV ac, 25 kV ac or 50 kV ac electrification voltages. The 12.5 kV and 50 kV systems are not commonly used, while the 25 kV system has become the de facto world standard. Typical substation spacing for 25 kV direct-fed ac electrification systems is approximately 25-30 km. With traction power substations located at such wide spacing, a strong and highly reliable utility connection is required, typically at 115 kV or 230 kV input voltage. Further, to serve the rolling stock power demand over the long distance, typically the substations are rated at 30 MVA to 60 MVA.

In contrast to the dc-powered systems operating at lower voltages, the same 10-car EMU would draw under acceleration 720 A at 12.5 kV, 360 A at 25 kV, and 180 A at 50 kV. These currents can be supplied much more readily by a conventional catenary system without the danger of OCS conductor overheating.

At substations and at approximate mid-point between substations, phase breaks are installed in the catenary system to separate sections of catenary system operating at different phases. Adjacent to the mid-point catenary phase breaks; wayside switching stations are installed to enable switching operations of the catenary system in the event of substation failure. Paralleling stations may be employed between substations and switching stations to improve voltage profile along the system and provide for better current sharing between conductors of adjacent tracks.

Power from the substation supply transformers is delivered to the catenary circuits via medium voltage switchgear installed in buildings or by outdoor, pole-mounted circuit breakers.

A typical ac direct-fed system configuration is presented in Figure 2-1.

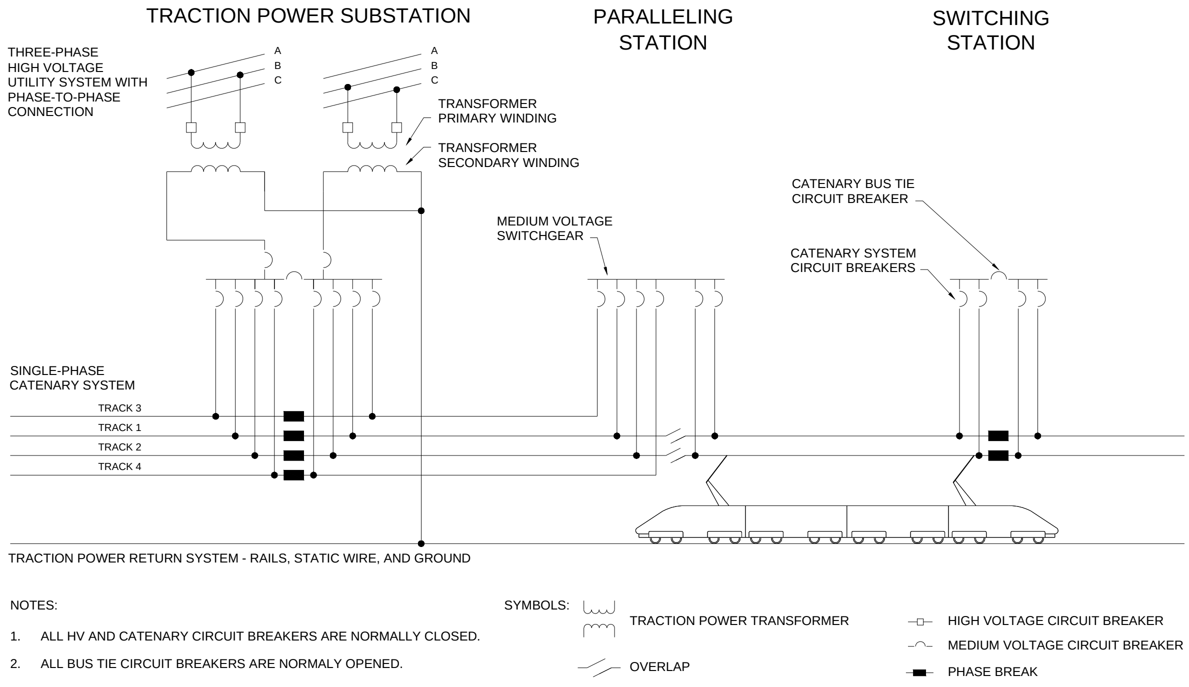

***Figure 2-1 – Typical Configuration of AC Direct-Fed Electrification System***

## *Autotransformer-Fed System*

Modern autotransformer-fed systems operate at 2x12.5 kV ac or 2x25 kV[4] ac electrification voltages, with the 2x25 kV system being the world standard. Typical substation spacing for 2x25 kV direct-fed ac electrification systems is approximately 50-60 km. Similarly to the direct-fed system, with the traction power substations located at wide spacing, a strong and highly reliable utility connection is required, typically at 115 kV or 230 kV input voltage utilizing commercial frequency of 60 Hz. Further, to serve the rolling stock power demand, typically the substations are rated at 40 MVA to 80 MVA.

The current demands in the catenary system are comparable to the direct-fed system discussed above.

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[4] It should be noted that for the 2x25 kV autotransformer-fed system the autotransformer voltage ratings are as follows: primary winding 50 kV (feeder-to-catenary), and secondary winding 25 kV (catenary-to-rail). Since the feeder-to-rail and catenary-to-rail voltages are both 25 kV, the system gained the name 2x25 kV. Because of almost universal acceptance of the name in the industry, the autotransformer-fed system will be referred to as 2x25 kV in this study. Similarly, a direct-fed system, being installed with catenary system only, can be referred to as 1x25 kV system or 1x50 kV system. This nomenclature can be simplified to 25 kV or 50 kV system.

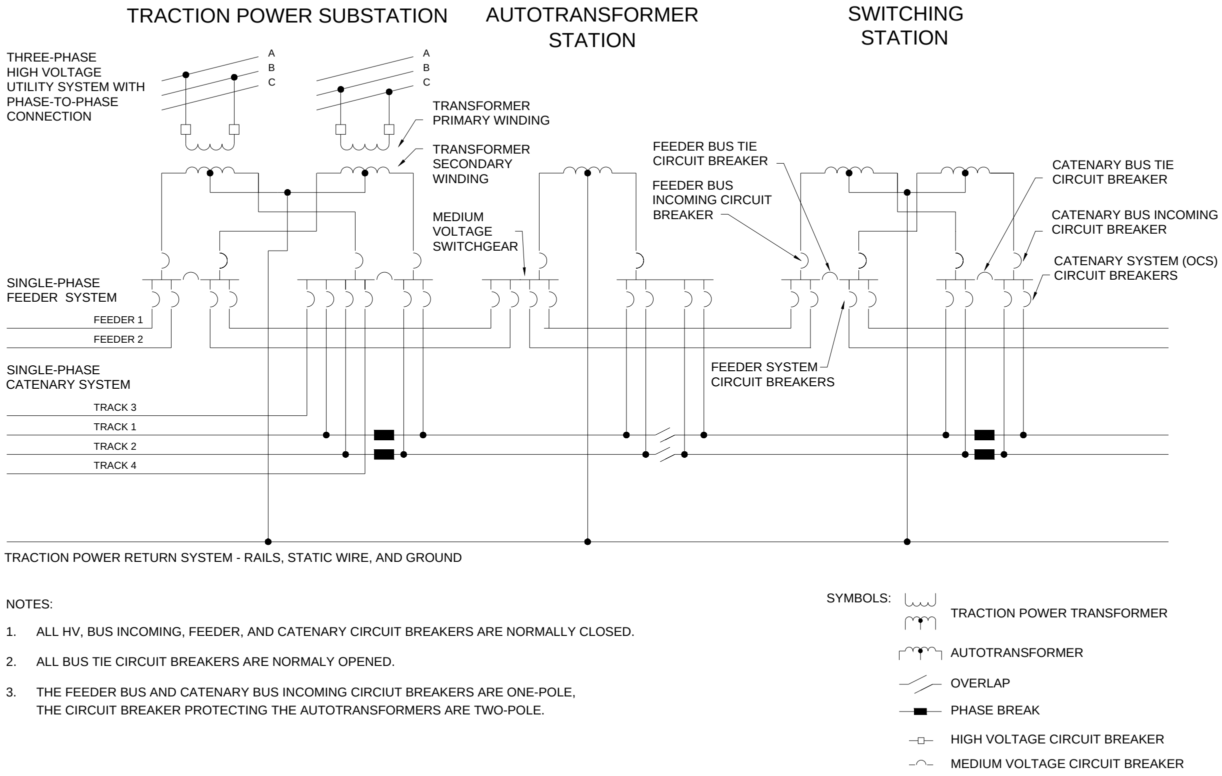
The substation transformer secondary windings are wound with a center tap which is grounded and connected to the return system rails. For example, in a 2x25 kV autotransformer system, the transformer secondary winding is 50 kV and is connected to the feeder and the catenary circuits via switchgear or circuit breakers. The center tap grounding results in feeder-to-rail voltage of 25 kV and catenary-to-rail voltage of 25 kV.

At regular intervals, 8-12 km apart, autotransformer stations are installed, typically with one or two autotransformers. The purpose of the autotransformers is to transform the 50 kV feeder-to-catenary voltage to 25 kV catenary-to-ground voltage. In this manner, the power is distributed along the system at 50 kV and the power is utilized by the trains at 25 kV. This is very advantageous, as the autotransformer-fed system can achieve substation spacing comparable to 50 kV direct-fed systems. With the train utilization voltage of 25 kV, clearances for electrification system operating at 50 kV are not necessary.

Similarly to the direct-fed system, phase breaks are installed in the catenary system at substations and at approximate mid-point between substations, to separate sections of catenary system operating at different phases. The feeder system is provided with a gap for the same reason. Adjacent to the mid-point catenary phase breaks and the feeder gaps; wayside switching stations are installed to enable switching operations of the catenary and feeder systems in the event of substation failure.

Power from the substation supply transformers and autotransformers is delivered to the catenary and feeder circuits via medium voltage switchgear installed in buildings or by outdoor, pole-mounted circuit breakers.

A typical ac autotransformer-fed system configuration is presented in Figure 2-2.



NOTES:

1. ALL HV, BUS INCOMING, FEEDER, AND CATENARY CIRCUIT BREAKERS ARE NORMALLY CLOSED.
2. ALL BUS TIE CIRCUIT BREAKERS ARE NORMALY OPENED.
3. THE FEEDER BUS AND CATENARY BUS INCOMING CIRCIUT BREAKERS ARE ONE-POLE, THE CIRCUIT BREAKER PROTECTING THE AUTOTRANSFORMERS ARE TWO-POLE.

*Figure 2-2 – Typical Configuration of AC Autotransformer Electrification System*

## Booster-Transformer System

Booster transformers[5] can be used in the direct-fed system to reduce electromagnetic interference (EMI). The purpose of the booster transformers is to cause the catenary and return currents flow as closely as possible to each other so that they cancel their external effects and reduce the EMI with wayside equipment. The higher number of booster transformers yields higher level of mitigation, but impedance of the distribution system correspondingly increases, which is a distinct system disadvantage. The position of the return feeder can be selected for greatest mitigation effects.

Although there are several booster transformer systems operating at single-phase, ac systems at the commercial frequency, the booster transformer system, however, has not been used in recent years. This is due to the fact that more and more communications circuits are being replaced by digital and fibre optic systems immune to EMI and signalling system manufacturers are capable of providing equipment specially designed and built for electrified railroads and resistant to the effects of EMI. Therefore, the system is considered as inappropriate for the Metrolinx system electrification and is removed from further consideration in this study.

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[5] Booster transformers are 1:1 current transformers installed between the catenary system and the booster feeder at insulated overlaps along the distribution system, usually at 2-3 km spacing.

### *AC Electrification Systems Operating at Non-Commercial Frequency*

There are existing electrification systems in the USA operating at a non-commercial frequency of 25 Hz, including the Amtrak Northeast Corridor from Washington, D.C. to New York, NY and the Harrisburg Line, and the SEPTA Regional Rail Lines in Philadelphia and its suburbs. In Europe, specifically in Germany, Austria, Switzerland, Norway and Sweden, the electrification systems operate at a non-commercial frequency of $16^2/_3$ Hz.

These non-commercial frequencies were chosen at the time of beginning of electrification, early last century. At that time, the commutator-equipped universal motor was the traction motor of choice due to its high starting torque. However, at the commercial frequency, the universal motor commutator would experience sparking and would require very high maintenance. Also, the voltage drop across the motor field winding and armature would be too great for the motor to operate efficiently. Since power electronic control equipment did not exist, as yet, lowering the frequency was the only practical option available for use of the universal motor at reasonable maintenance cycle, making electrification economically feasible.

To lower the frequency from 60 Hz to 25 Hz in the United States, or from 50 Hz to $16^2/_3$ Hz in Europe, it was necessary to employ rotary frequency converters in the traction power substations. The original frequency converters, some of which are still in use today, consisted of motor-generator sets. The motors are connected to the utility power system at commercial frequency and the generators produce traction power at non-commercial frequency for use by the trains. As the aging rotary converters are being retired, many countries, including the United States are replacing them with modern static frequency converters. The static frequency converters convert the frequency with power electronics devices (thyristors or IGBTs[6]), contain no moving parts, and therefore, are less expensive to maintain than the rotary frequency converters.

Today, there is no reason to use other than commercial frequency for a new electrification system. Suitable on-board power electronics equipment is available to condition and control power[7] for use by the traction motors. Any wayside frequency conversion equipment, such as the previously discussed custom-manufactured static or rotary frequency converters, would be too expensive and not commercially viable. The commercial frequency ac electrification systems evaluated above are the world standard for networks of Metrolinx's size and offer superior efficiency and smaller land footprint for substations. Therefore, alternative electrification frequencies are not considered as suitable for Metrolinx electrification and are removed from further consideration in this study.

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[6] Insulated Gate Bi-Polar Transistors

[7] The single-phase ac power picked-up by the pantograph is rectified to dc and, subsequently, inverted to three-phase variable voltage variable frequency (VVVF) ac power for supply of ac induction motors. The VVVF is very efficient means of controlling induction motors, which are today the motors of choice due to their low maintenance requirements.

### *Combination of AC and DC Electrification Systems*

The potential electrification of Union Station presents some unique challenges to provide continuous supply of traction power as trains navigate through the complex interlocking arrangements approaching the passenger platforms. One alternative would be to install a third rail system within the western and eastern Union Station throat areas.

It is possible to equip some parts of the system with ac electrification and some of the system with dc electrification. This could be accomplished in many different ways; examples of some potential combined systems are presented below:

- Equipping some GO track segments with ac catenary and some segments with dc catenary or dc third rail
- The high traffic density lines, such as the Lakeshore Line, could be equipped with ac electrification system and the low density branch lines with dc electrification catenary systems
- The area adjacent to Union Station could be equipped with dc third rail electrification system and the remainder of the system with the ac electrification catenary system
- Equipping some GO track segments with ac catenary, other segments with dc third rail and the core of the system around Union Station with both systems to avoid requirement for dual-power rolling stock.

The first approach is not recommended for the following reasons:

- Dual-power ac and dc rolling stock would be required as a trip from one of the lightly used lines to Union Station would require a power supply changeover.
- Dual-power ac and dc rolling stock is more expensive than a single-power rolling stock.
- Spare parts inventory would be higher for the dual-power rolling stock in comparison to single-power rolling stock.

The second approach is not recommended for the following reasons:

- The dc EMUs would not be light as would be expected on dc only electrification system. The EMUs would have to be built to the same mainline railroad standards as the ac rolling stock for the dc EMUs to be able to comingle with 10-car trains in the shared trackage approaching Union Station.
- The mix of two traction power systems in the Union Station area and its approaches would complicate signalling installations and would mandate significant additional testing for electromagnetic interference issues.
- Two sets of spare parts would be required for the ac and dc rolling stock.
- The dual traction power supply systems would substantially increase capital costs in comparison to one system.
- The visual impact of the OCS would remain

Further, both approaches have the following disadvantages:

- The solution would not be cost-effective. For example, having electrified the Lakeshore Line at 25 kV ac, the Richmond Hill Line could probably be operated as a direct-fed ac system with no additional ac power supply substations. In the worst case, one ac autotransformer station, costing approximately $5 million, may be needed. Since the Richmond Hill Substation is over 30 km long, for dc electrification approximately 20 substations would be needed, costing approximately $30-40 million.
- The dc substation requirements are significantly more extensive (in terms of both land and capital cost) than corresponding ac system requirements.
- Third rail installation would be very labour intensive, especially in segments of the GO network with more than two tracks, as approximately every fifth tie would have to be replaced with longer tie for third rail insulator installation.
- Third rail would limit train speeds to 130 km/h, or less, in the dc electrified territory due to potential gapping/arching issues.
- Third rail adjacent to at-grade highway crossings is highly undesirable due to safety concerns. Grade separation at these locations would need to be considered, potentially adding substantial cost to the electrification project.
- DC system, either catenary or third rail, would need to be equipped with stray current and corrosion control measures
- Two sets of spare parts would be required for the two traction power supply and distribution systems.
- O&M costs would be higher

Further, it should be noted that with Union Station's complex switch and crossover designs, the third rail could not be continuous. In a locomotive application, where all traction power is typically collected by one or two contact shoes on the locomotive, this could lead to many transitions between powered and unpowered operation. Each unpowered segment is an opportunity for the train to become stranded. EMU consists, with power collected at every car, could travel through these gaps better, as at least part of the train would be powered at all times.

Also, a 10-car train requires relatively high power demand during acceleration, and as already discussed, at the low voltage of the third rail, the high power demand results in high current. Such high current would be very difficult to pick up by a single locomotive current collector, and would essentially eliminate the electric locomotive and dual-mode locomotive technology options if the Union Station approaches must be third rail powered.

Therefore, combination of ac and dc electrification systems is not considered suitable for Metrolinx electrification and will be removed from further consideration in the Electrification Study.

### *Alternative System Technologies and Enhancements*

As described in the Rolling Stock Technology Assessment report, hybrid propulsion systems use on-vehicle energy storage to smooth out drive load transients and save energy consumption. Similar energy saving opportunities may be available for wayside installation in the form of energy storage devices. Further, alternative energy may be available from wayside hydrogen fuel cell power generation.

### Wayside Energy Storage

Electric locomotives and EMUs can use regenerative braking to return excess energy to the traction power system where the energy can be used by other trains operating on the system. In the event that there are no trains in the vicinity of the braking train, the energy can be stored in wayside energy storage devices until it is needed to support local, heavy train acceleration. Several companies have wayside energy storage devices in a prototype stage, using flywheels, batteries, or ultra-capacitors. Wayside installations are less weight and space sensitive than on-vehicle systems, although losses in transmission of the power to and from the energy storage devices have to be considered, particularly in ac electrification applications.

### Wayside Hydrogen Fuel Cell Power Generation

Wayside hydrogen fuel cells could be designed to power traction power substations supplying traditional OCS to support electric locomotive or EMU operation. The wayside installations could be distributed and sized as required, without the same regard for weight and packaging as would be required if installed on vehicles. The hydrogen fuel supply would be more closely controlled and protected than on-board of vehicles, and could be supplied by a pipeline from a central source. Although hydrogen fuel cells are relatively efficient, consideration needs to be given to efficiency of conversion of the fuel cell output to electrification voltage. There are no known prototypical or revenue systems of this type serving rail transit or railroad line systems at present.

### Technology Availability

The wayside energy storage devices and the hydrogen fuel cell power generation are considered as emerging technologies at this time and will be removed from further consideration in the Electrification Study.

# 3. ELECTRIFICATION TECHNOLOGY ASSESSMENT

## 3.1. Factors Influencing Electrification System Choice

In order to identify a “short list” of technologies for further assessment, the following criteria were used in the evaluation:

- Is the technology **proven**?
- Is the technology **technically viable**?
- Is the technology **commercially viable**?
- Is the technology **compatible with the Reference Case infrastructure?**
- Is the technology **compatible with the Reference Case service levels?**

## 3.2. Proven Technology

The dc and ac electrification systems identified in this report are proven technologies, with many miles of each type of system operating every day in Canada, United States and overseas.

Wayside energy storage and hydrogen fuel cell power generation are both emerging technologies. Flywheel was tested by Metro-North in Far Rockaway, NY, supercapacitors were tested by Tri-Met in Portland, OR, and batteries are being tested by RTD in Sacramento, CA with good technical results. It should be noted that all three system are 750 V dc. To our knowledge no such testing has been performed on ac electrification systems. It can be expected that the ac to dc rectification and the dc to ac inversion would substantially decrease the device efficiency.

## 3.3. Technically Viability

DC electrification system utilizing OCS would have insufficient power supply capability with OCS conductor overheating very likely. DC system with third rail could be used, but the system is not preferred due to safety concerns at grade crossings and speed limitation.

AC electrification systems, direct-fed and autotransformer-fed, operating at commercial and non-commercial frequency are both technically viable. The booster-transformer system is not preferred due to relatively short substation spacing distances. Similar degree of EMF/EMI mitigation can be achieved with autotransformer system which has the advantage of significantly longer substation spacing

Wayside energy storage and wayside hydrogen fuel cell power generation are not technically viable at present due to being emerging technologies unproven in ac electrification systems.

## 3.4. Commercial Viability

DC systems would require a large number of traction power substations throughout the system and such high number of facilities would make dc electrification commercially not viable. AC electrification systems operating at non-commercial frequency would be very expensive and commercially not viable due to requirement for rotary or static frequency converters to be installed in traction power substations.

The 50 kV electrification system requires higher electrical clearances than 25 kV system. Therefore, the number of locations requiring civil modifications would be substantially higher for 50 kV electrification system with the risk that the 50 kV would be uneconomical.

Combination of ac and dc electrification systems would be expensive due to dual system construction, dual power rolling stock, and requirement for two sets of spare parts.

## 3.5. Compatibility with the Reference Case Infrastructure

Electric propulsion, whether locomotive or EMU, requires a complete traction electrification system. This consists of traction power substations, an OCS or third rail, switching stations, paralleling stations and associated equipment.

Since the infrastructure required will vary with technology selection, different electrification systems will have different cost and property acquisition implications. For dc electrification system relatively small substations are required, approximately 5x15 m at frequent intervals in order of kilometres. For ac electrification large substations, 50x80m, are required at approximate spacing of 40-60 km.

For dc third rail system to be built, each 5th railroad tie has to be replaced with a longer tie for mounting of electrical insulators supporting the third rail. This will be particularly challenging in the complex interlocking areas of Union Station. For ac electrification new poles and portal structures will be required to support the OCS system with the corresponding visual impact.

## 3.6. Compatibility with the Reference Case Service Levels

Each technology considered in this report is compatible with the Reference Case passenger traffic levels.

### *Summary*

Applying the five screening criteria identified earlier in the report, the candidate technologies are compared in Table 3-1. The criteria used in the assessment include:

*Table 3-1 – Summary Comparison of Electrification System Technology Screening Criteria*

| Technology Type | Proven Technology | Technical Viability | Commercial Viability | Compatibility with Reference Case Infrastructure | Compatibility with Reference Case Service Levels |
|---|---|---|---|---|---|
| DC Electrification Systems | Yes | Yes | No | No | Yes |
| AC Electrification Systems at Commercial Frequency | Yes | Yes | Yes | Yes | Yes |
| AC Electrification Systems at Non-Commercial Frequency | Yes | Yes | No | No | Yes |
| Combination of AC and DC Electrification Systems | Yes | Yes | No | No | Yes |
| Wayside Energy Storage | No | No | No | Yes | Yes |
| Wayside Hydrogen Fuel Cell Power Generation | No | No | No | Yes | Yes |

The five screening criteria yield a “short list” of electrification technologies appropriate and suitable for Metrolinx’s GO system electrification which can be taken forward for further assessment. The technologies include ac electrification systems operating at commercial frequency:

- Direct-fed system operating at 1x25 kV ac electrification voltage, 60 Hz
- Autotransformer-fed system operating at 2x25 kV ac electrification voltage, 60 Hz
- Direct-fed system operating at 1x50 kV ac electrification voltage, 60 Hz

### *Comparison of Selected Technologies*

A qualitative comparison of the electrification technologies selected for the GO network electrification is presented in Table 3-2.

*Table 3-2 – Summary of Electrification Technologies Suitable for GO Network Electrification*

| **Parameter** | **1x25 kV Direct-Fed System** | **1x50 kV Direct-Fed System** | **2x25 kV Autotransformer-Fed System** |
|---|---|---|---|
| **Traction Power Supply System** | | | |
| Typical Substation Spacing | 25-30 km | 50-60 km | 40-45 km |
| Typical Substation Rating | 2x20 MVA | 2x40 MVA | 2x40 MVA |
| Substation Real Estate Requirement | 40x70m | 40x70m | 50x80 m |
| **Traction Power Distribution System** | | | |
| OCS Complexity | Low | Low | High, Feeder Required |
| OCS Clearance Requirements | Low | High | Low |
| Autotransformer Stations | No | No | Yes, 10x18 m |
| Switching Stations | Yes, 10x18 m | Yes, 10x18 m | Yes, 10x18 m |
| **Competitive Equipment Availability** | | | |
| Proven Suppliers | Yes | No | Yes |
| Proven Equipment | Yes | No | Yes |
| Adequate Competition | Yes | No | Yes |

| | | | |
|---|---|---|---|
| **Cost** | | | |
| Capital Cost | Medium | Low | High |
| Maintenance Cost | Medium | Low | High |
| **Power Demand and Energy Losses** | | | |
| Substation Maximum Demand | Low | High | High |
| Energy Losses | High | Low | Medium |
| **External Impacts** | | | |
| Electromagnetic Fields (EMF) | High | High | Low |
| Electromagnetic Interference (EMI) | High | High | Low |
| Rail-to-Ground Voltages | High | High | Low |
| Visual Impact | Medium | Low | High |
| Utility Interface | High | Low | Low |

Both, 1x25 kV and 2x25 kV systems can co-exist together in a single system, and it is possible, for example, to electrify the major, high capacity parts of the GO network using autotransformer-fed system while electrifying lightly loaded route extremities using direct-fed system. Simulation modeling of the traction electrification system, to be performed later in the study, will determine the parts of the system where each electrification system is the most appropriate.

As discussed earlier, 25 kV and 50 kV electrification voltages can be used; however, the 1x25 kV direct-fed system and 2x25 kV autotransformer-fed system are considered more suitable for the GO system electrification due to lower clearance requirements than necessary for the 50 kV system. The 1x50 kV direct-fed system is a technically viable option, however, the available clearances substantially increase the risk of the system being economically unfeasible. Also, considering that there are relatively low number of systems around the world operating at 50 kV, a competitive pricing on 50 kV rolling stock may not be offered by major rolling stock suppliers.

The advantages of the 2x25 kV autotransformer-fed system include the capability of transmitting power along the railroad at 50 kV, powering the trains at 25 kV, long substation spacing, and some mitigation of potential electromagnetic fields and electromagnetic interference effects. The shorter substation spacing for the 25 kV direct-fed system is a disadvantage in areas where access to, or capacity of, utility power sources is limited.

Hydro One indicated a preference for connections to its 230 kV network in the central Toronto area. The 230 kV transmission lines in close proximity to the rail network that have sufficient supply capacity are located near Horner Ave and Kipling Ave, approximately 14 km west of Union Station and near St. Clair Ave East and Warden Ave, approximately 14 km east of Union Station.

### *Recommendation*

Therefore, the technology selected and recommended for development of conceptual design and cost estimate of the GO system electrification is:

- Autotransformer-fed system operating at 2x25 kV ac electrification voltage, 60 Hz

The 2x25 kV autotransformer-fed system is being used extensively overseas, and in the US the system is used by Amtrak on the Northend Electrification system from New Haven, CT to Boston, MA, a distance of 156 miles. The reason for selecting the autotransformer-fed system was the limited availability of utility high voltage power transmission feeds. A direct-fed system would have required power supply by 12 substations, and this level of utility supply was not available. The autotransformer-fed system has been built with only four supply substations.

Other examples of commuter railroads in US being powered by the autotransformer systems in revenue service include:

- New Haven Line from Mount Vernon, NY to New Haven, CT operating at 2x12.5 kV, 60 Hz, and owned by Metro-North Railroad (MNR)
- New Haven Line from Gate, NY to New Rochelle, CT, operating at 2x12.5 kV, 60 Hz, and owned by Amtrak
- Morris & Essex Line from Kearny Junction in Kearny, NJ (just outside New York, NY) to Dover, NJ and Gladstone, NJ operating at 2x25 kV, 60 Hz, and owned by New Jersey Transit (NJT)
- Commuter line network in Philadelphia and its suburbs operating at unique 24 kV/12 kV, 25 Hz, and owned by Southeastern Pennsylvania Transportation Authority (SEPTA)

The 2x25 kV autotransformer-fed system is also being employed in the design for electrification of the Caltrain commuter route from San Francisco to San Jose.

Examples of electrifications systems around the world are presented in Appendix B.

## APPENDIX 6A - DOCUMENT DEFINITIONS AND GLOSSARY OF TERMS

| **Term** | **Definition** |
|---|---|
| **A** | |
| Autotransformer-Fed System | Electrification system consisting of substations feeding along-track feeder and catenary systems. The feeder-to-catenary voltage is stepped-down to catenary-to-rail voltage at autotransformer stations and switching stations located along the system by the means of autotransformers. Since the feeder-to-catenary voltage is typically two to three times the catenary-to-rail voltage, longer substation spacing can be achieved than for a direct-fed system not using autotransformers. |
| Autotransformer Station | Station with one or more autotransformers used for transforming the feeder-to-catenary voltage to catenary-to-rail voltage. Autotransformer stations contain circuit breakers or switchgear line ups and effectively parallel the feeder and catenary circuits. Feeder and catenary paralleling achieves better current sharing between the conductors, lowers the effective impedance between substations and trains, and results in lower voltage drop. |
| **C** | |
| Cab Car | A passenger carrying railcar that also has a control stand from which a trained operator can control the propulsion and braking of the consist. |
| Catenary System | Overhead power distribution system providing traction power to electric locomotives and EMU cars. |
| Catenary System Supporting Structures | Poles, towers, bridges, or other stationary structures used for supporting a catenary system including foundations, anchors, guys, braces, and similar reinforcing attachments. |

| **Term** | **Definition** |
|---|---|
| Center-Fed System | Electrification system in which substations feed sections of catenary at their center to minimize catenary voltage drop. In the event that the center-fed system operates at commercial frequency, the system substations would have one or two single-phase traction power transformers connected phase-to-phase to the three-phase power utility network. |
| Conceptual Design | A generalized plan describing design requirements and used as a guide to preliminary design. |
| Coach Car | A passenger carrying railcar without an operator's control cab. A coach car is typically simpler than a cab car. |
| Contact Wire | Conductor in contact with pantograph used by locomotives and EMU cars to collect train power requirements. The conductor is suspended from messenger or auxiliary messenger by the means of hangers and contact wire clamps. |
| Cross-bonds | Connections between impedance bonds to reduce effective resistance of the traction power return system and to return the currents back to the substation. |
| **D** | |
| Direct-Fed System | Electrification system consisting of substations feeding a catenary system. |
| Distribution | Delivery of power from transmission system to end-use customers at voltages greater than 110 V and less than 69 kV. |
| **E** | |
| Electric Multiple-Unit | A railroad car equipped with its own electrical propulsion system, braking system, and auxiliary devices. |
| Electric Traction | A means for propulsion of railroad vehicles whereby power is provided by electrical energy transmitted from a remote source |

| **Term** | **Definition** |
|---|---|
| | through a traction power distribution system. |
| Electrification System | Facilities and structures required to provide electrical power to the trains. |
| **F** | |
| Final Design | A design stage during which final specifications, contract drawings, schedules, and cost estimates are prepared for a specific construction project. |
| Fluctuation of Power Demand | Because of frequent train acceleration and deceleration, and due to sudden changes in track geometry, train power demand has a highly fluctuating pattern. |
| Fundamental Frequency Component | The fundamental frequency is the first harmonic. |
| **G** | |
| Grounded Equipment | Equipment connected to the conducting mass of the earth via ground rods, grounding grid, or both, to ensure an immediate discharge of electrical potential without danger. |
| **H** | |
| Harmonics | Voltages and currents at frequencies other than the fundamental system frequency. Harmonics are caused by non-linear circuit components such as diodes and thyristors. |
| Harmonic Distortion | Voltage and current waveform distortion due to the harmonic currents generated by non-linear equipment, such as thyristor-controlled equipment on board the rolling stock or in substations. |
| **I** | |

| Term | Definition |
|---|---|
| Impedance Bond | An iron-core coil of low resistance and relatively high reactance used to confine signalling current to its own track circuit and to provide a continuous path for the traction return current around insulated joints to substation. |
| Insulated Gate Bi-polar Transistor (IGBT) | A semiconductor device acting as an electronic switch capable of switching current on and off with greater efficiency and lower harmonics than thyristor. |
| **M** | |
| Messenger Wire | Upper wire in a catenary system from which the contact wire is suspended by means of hangers. |
| Milepost | An identifier for a given location along a railroad line. Mileposts may or may not be located exactly one mile apart and may not be sequentially numbered. |
| Multiple-Unit | A railroad car equipped with its own propulsion system, braking system, and auxiliary devices. |
| **P** | |
| Pantograph | Locomotive or EMU collector of traction power from overhead catenary system. |
| Pantograph Head | Uppermost part of the pantograph fitted with the current collector which slides on the bottom of contact wire. |
| Paralleling Station | Stations containing circuit breakers or switchgear line ups used for paralleling of traction power distribution system circuits. Catenary paralleling achieves better current sharing between the conductors, lowers the effective impedance between substations and trains, and results in lower voltage drop. |
| Phase Break System | System consisting of on-board and wayside equipment enabling locomotives or EMU cars automatic, or “on the fly”, negotiation of |

| Term | Definition |
|---|---|
| | phase breaks by ramping propulsion power down on approach and ramping propulsion power up upon crossing the phase break. |
| Power Demand Analysis and Load-Flow Study | A computer-aided study using specially written computer program to calculate the combined performance of the traction power supply and traction power distribution systems with operating trains. The study results include catenary system voltages, catenary system currents, substation power demand requirements and substation energy consumption. |
| Power Factor | Ratio of useful (real) power to total (apparent) power. Power factor is dependent on the rolling stock propulsion system design. With conventional propulsion systems using thyristor-controlled rectifiers and dc traction motors, the power factor is low at low trains speeds and improves as the speed increases. Using modern IGBT-based propulsion systems with ac motors, a power factor close to unity can be maintained throughout the speed range. |
| Preliminary Design | A design stage at which specifications and drawings clearly show all major design elements and define requirements for final design. Design calculations are substantially complete, cost estimates are detailed to an extent compatible with the level of design, and a preliminary construction sequence schedules are prepared. |
| Prime Mover | The core source of tractive power on a non-electrified railcar. For a diesel locomotive, the prime mover is traditionally a single large diesel engine. More modern designs, including DMUs, tend to use several medium sized diesel engines to create the traction power. A fuel cell can also be a prime mover. |
| **S** | |
| Simple Catenary System | A system of messenger wire supporting a contact wire by the means of hangers. The system is suitable for medium speed to high-speed applications. |
| Single Contact Wire System | A system of single contact wire without messenger or auxiliary messenger wire. The system is suitable for tramway system, yard, and shop applications. |

| Term | Definition |
|---|---|
| Station Dwell Time | That amount of time during which a train is stopped to open and close doors and receive and/or discharge passengers. |
| Substation | Traction power supply facility. Typical traction power substation includes power utility interface equipment; disconnect switches, circuit breakers, traction power transformers, switchgear, control equipment, and auxiliary system. Special equipment, such as harmonic filtering and power factor control equipment may be installed in substations, as required. |
| Switching Station | Stations containing circuit breakers or switchgear line up used for switching section of distribution system during substation outage conditions and for paralleling distribution system circuits. |
| **T** | |
| Thyristor | A semiconductor device acting as an electronic switch capable of switching current on and off. |
| Track Circuit | An electrical circuit formed by the running rails of the track. The purpose of the track circuit is to detect the presence of rolling stock on a given section of track when the track circuit is short-circuited by wheels and axles. |
| Traction Electrification System | Traction power supply, traction power distribution, and traction power return systems. |
| Traction Motor | An electric motor that directly drives one or more axles to propel a railcar along the tracks. |
| Traction Power Distribution System | Overhead catenary system, overhead trolley system or contact rail system. Each may be accompanied by along track overhead or underground feeders. |
| Traction Power Return System | Rails, impedance bonds, cross-bonds, earth, and in the case of ac electrification, also static wire. |

| **Term** | **Definition** |
|---|---|
| Traction Power Supply System | Traction power substations located at predetermined spacing along the route. |
| Transmission | Delivery of power at a voltage of 69 kV or higher from generating plants across interconnected high voltage facilities to points where the power enters distribution system. |
| **U** | |
| Unbalance | Voltage and current unbalance occurs when a three-phase system supplies a phase-to-phase load. The utility system voltage and current unbalance can be limited by alternating substation transformer primary connections to different phases of the utility power system, e.g., A-B, B-C, C-A, A-B, and so on. |
| **V** | |
| Voltage Flicker | Mathematically, the voltage flicker is defined as a change in voltage divided by the voltage, and is usually expressed in percent. |
| **A** | |
| A | Ampere |
| AAR | Association of American Railroads |
| A, B, C | Designation of Three-Phases of Utility Power System |
| ac | Alternating Current |
| AMT | Agence Métropolitaine de Transport |
| APS | Alimentation Par Sol |

| Term | Definition |
|---|---|
| APTA | American Public Transit Association |
| AREMA | American Railway Engineering and Maintenance-of-Way Association |
| AT | Autotransformer |
| ATF | Autotransformer-Fed |
| ATS | Autotransformer Station |
| AW0 | Empty Car Operating Weight, Filled with Consumables |
| AW1 | AW0 Weight Plus Full Seated Passenger Load And Train Crew |
| AW2 | AW1 Weight Plus Standees at 4 per square meter of Available Floor Space (One Passenger per 2.7 sq. ft.). Structural Mean Fatigue Load, Propulsion and Dynamic Braking Performance Load. |
| AW3 | AW1 Weight Plus Standees at 6 per square meter of Available Floor Space (One Passenger per 1.8 sq. ft.). Friction Braking Performance Load. |
| AW4 | Either 105% of AW3 or AW1 Weight Plus Standees at 8 per square meter of Available Floor Space (One Passenger per 1.35 sq. ft.). Structural Design Load, not Contemplated For Revenue Operation. |
| **B** | |
| BE | Braking Effort |
| **C** | |
| C | Capacitance |

| Term | Definition |
|---|---|
| CEPA | Canadian Environmental Protection Act |
| CFM | Cubic Feet per Minute |
| CFR | Code of Federal Regulations (United States) |
| cmil | Circular mil |
| CN | Canadian National Railway |
| CNG | Compressed Natural Gas |
| CO | Carbon Monoxide |
| CP | Canadian Pacific Railway |
| CSA | Canadian Standards Association |
| CSI | Cab Signal Interference |
| **D** | |
| dB | Decibel |
| dBµV/m/MHz | Decibel Microvolt per Meter per Megahertz, Unit for Measurement of Electric Field Strength |
| dc | Direct Current |
| DEMU | Diesel-Electric Multiple Unit |
| DF | Direct-Fed |

| **Term** | **Definition** |
|---|---|
| DMU | Diesel Multiple Unit |
| DMMU | Dual-Mode Multiple Unit |
| **E** | |
| EC | Environment Canada |
| EIS | Environmental Impact Statement |
| Eff | Efficiency |
| ELF | Extremely Low Frequency |
| EMF | Electromagnetic Fields |
| EMI | Electromagnetic Interference or Electromagnetic Induction |
| EMR | Electromagnetic Radiation |
| EMU | Electric Multiple Unit |
| EPA | Environmental Protection Agency (United States) |
| ESI | Electrostatic Interference or Electrostatic Induction |
| **F** | |
| FCC | Federal Communications Commission (United States) |
| FRA | Federal Railroad Administration (United States) |

| Term | Definition |
|---|---|
| **G** | |
| G | Giga, $10^9$ |
| g/bhp-h | Grams/Brake Horsepower-Hour |
| **H** | |
| HC | Hydrocarbons |
| HDMU | Hybrid Diesel Multiple Unit |
| HEP | Head-End Power |
| hp | Horsepower |
| HV | High Voltage |
| HVAC | Heating, Ventilation and Air Conditioning |
| Hz | Hertz |
| **I** | |
| IEEE | The Institute of Electrical and Electronics Engineers, Inc. |
| IGBT | Insulated Gate Bi-Polar Transistor |
| IPT | Inductive Power Transfer |
| **J** | |

| Term | Definition |
|---|---|
| j | Complex Number Operator |
| **K** | |
| k | kilo, $10^3$ |
| kA | Kiloampere |
| kcmil | Kilo Circular Mil |
| kV | Kilovolt |
| kVA | Kilovolt-Ampere |
| kVAr | Kilovolt-Ampere Reactive |
| kW | Kilowatt |
| kWh | Kilowatt-Hour |
| kWh/ckm | Kilowatt-Hour per Car-Kilometre |
| kWh/cm | Kilowatt-Hour per Car-Mile |
| **L** | |
| L | Inductance |
| ICNIRP | International Commission on Non-Ionizing Radiation Protection |
| LHC | Locomotive-Hauled Coaches |

| **Term** | **Definition** |
|---|---|
| LNG | Liquefied Natural Gas |
| LV | Low Voltage |
| **M** | |
| M | Mega, $10^6$ |
| µ | micro, $10^{-6}$ |
| m | mili, $10^{-3}$ |
| Maglev | Magnetic Levitation |
| MHz | Megahertz |
| MP | Milepost |
| MPI | Motive Power Industries |
| MU | Multiple-Unit |
| MV | Medium Voltage |
| MVA | Megavolt-Ampere |
| MVAr | Megavolt Ampere Reactive |
| MW | Megawatt |
| MWh | Megawatt-Hour |

| Term | Definition |
|---|---|
| **N** | |
| N. C. | Normally Closed |
| NMHC | Non-Methane Hydrocarbons |
| N. O. | Normally Opened |
| $NO_x$ | Nitrogen Oxides |
| **O** | |
| O&M | Operation and Maintenance |
| OCS | Overhead Contact System |
| ONAN | Oil Natural Air Natural Transformer Cooling Method |
| **P** | |
| PCE | Pantograph Clearance Envelope |
| PM | Particulate Matter |
| PM10 | Particulate Matter Less than 10 Microns in Diameter |
| PTC | Positive Train Control |
| p. u. | Per Unit |
| **R** | |

| Term | Definition |
|---|---|
| R | Resistance |
| RF | Radio Frequency |
| RLC | Resistive-Inductive-Capacitive |
| ROW | Right-of-Way |
| RR | Railroad |
| **S** | |
| SWS | Switching Station |
| **T** | |
| T | Tesla, Transformer |
| TE | Tractive Effort |
| TES | Traction Electrification System |
| TH&B | Toronto, Hamilton and Buffalo |
| TPS | Traction Power Substation, Traction Power Supply |
| **V** | |
| V | Volt |
| V ac | Volts, Alternating Current |

| **Term** | **Definition** |
|---|---|
| V dc | Volts, Direct Current |
| VVVF | Variable Voltage Variable Frequency |
| **W** | |
| WHO | World Health Organization |
| **X** | |
| X | Reactance |
| XFRM | Transformer |
| **Z** | |
| Z | Impedance |

NOTE: Use hereafter of the terms “we”, “our” or similar means “Delcan/Arup Joint Venture team.”

## APPENDIX 6B - MODERN ELECTRIFICATION SYSTEMS

There are over 100,000 EMUs and Electric Locomotives operating around the world today. Figure B-1 shows the distribution of EMUs by continent. Europe and Asia operate the vast majority of EMUs, but several large North American transit agencies use them as well.

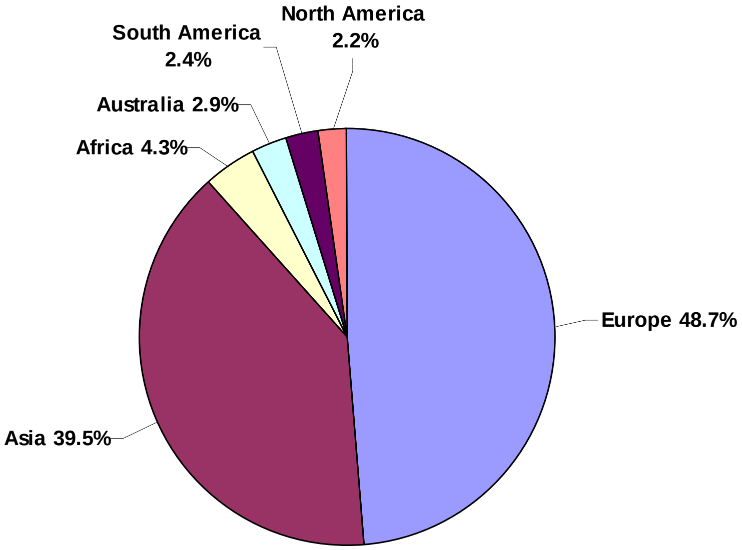

***Figure B-1 - Distribution of the World's EMUs by Continent***

A short list of modern electrification systems around the world is presented In Table B-1. The list is by no means comprehensive, and is intended to include examples of commuter, high-speed rail, and in some cases, freight electrification systems, already operating. All systems listed are operating at single-phase, using 25 kV electrification systems at commercial frequency of 60 Hz or 50 Hz, with source of power being provided by the local power utility companies.

Many countries have very extensive electrification networks operating and have further plans to extend their electrification systems in the future. In the following table, just one example per country is shown outside of North America.

*Table B-1 – Modern Electrification Systems around the World*

| | | |
|---|---|---|
| System | Deux Montagnes |  |
| Operator | AMT | |
| Country | Canada | |
| Service | Commuter | |
| Rolling Stock | EMUs | |
| Speed/Headway | 120 km/h/10-30 min | |
| Electrification | 25 kV ac, 60 Hz | |

| | | |
|---|---|---|
| System | Northend Electrification |  |
| Operator | Amtrak | |
| Country | USA | |
| Service | High-Speed Rail &<br>Commuter | |
| Rolling Stock | Power cars & trailers | |
| Speed/Headway | 232 km/h/30-60 min | |

| | | |
|---|---|---|
| Electrification | 25 kV ac, 60 Hz | |

| | | |
|---|---|---|
| System | North Jersey Coast Line |  |
| Operator | NJ Transit | |
| Country | USA | |
| Service | Commuter | |
| Rolling Stock | Electric LHC & EMUs | |
| Speed/Headway | 201 km/h/10 min | |
| Electrification | 25 kV ac, 60 Hz | |

| | | |
|---|---|---|
| System | West Coast Main Line |  |
| Operator | Network Rail | |
| Country | England | |
| Service | Intercity/Commuter/<br>Freight | |
| Rolling Stock | Electric LHC & EMUs | |
| Speed/Headway | 201 km/h/15-20 min | |
| Electrification | 25 kV ac, 50 Hz | |

|  |  |  |
|---|---|---|
| System | TGV (Train à Grande Vitesse) |  |
| Operator | French Railways (SNCF) |  |
| Country | France |  |
| Service | Intercity |  |
| Rolling Stock | Power cars & trailers |  |
| Speed/Headway | 300 km/h/20-30 min |  |
| Electrification | 25 kV ac, 50 Hz |  |

| | | |
|---|---|---|
| System | Madrid-Sevilla Line |  |
| Operator | Spanish Railway (RENFE) | |
| Country | Spain | |
| Service | Intercity | |
| Rolling Stock | Power cars & trailers | |
| Speed/Headway | 300 km/h/30 min | |
| Electrification | 25 kV ac, 50 Hz | |

| | | |
|---|---|---|
| System | Elektrichka |  |
| Operator | Russian Railways | |
| Country | Russia | |
| Service | Commuter | |
| Rolling Stock | EMUs | |
| Speed/Headway | 100 km/h/10-30 min | |
| Electrification | 25 kV ac, 50 Hz | |

| | | |
|---|---|---|
| System | Mumbai Rajdhani Express |  |
| Operator | Indian Railways (IR) | |
| Country | India | |
| Service | Intercity/Commuter | |
| Rolling Stock | Locomotive-Hauled Trains | |
| Speed/Headway | 87 km/h/15 min average | |
| Electrification | 25 kV ac, 50 Hz | |

| | | |
|---|---|---|
| System | Shinkansen |  |
| Operator | Japan Railways Group (JR) | |
| Country | Japan | |
| Service | Intercity | |
| Rolling Stock | EMUs | |
| Speed/Headway | 320 km/h/3 min | |
| Electrification | 25 kV ac, 50 Hz/60 Hz | |

| | | |
|---|---|---|
| System | Guangshen Railway |  |
| Operator | Guangshen Railway Company Limited | |
| Country | China | |
| Service | Intercity/Commuter / Freight | |
| Rolling Stock | EMUs | |
| Speed/Headway | 200 km/h/20-30 min | |
| Electrification | 25 kV ac, 50 Hz | |

| | | |
|---|---|---|
| System | Werribee Railway Line |  |
| Operator | Australian Railways | |
| Country | Australia | |
| Service | Commuter | |
| Rolling Stock | EMUs | |
| Speed/Headway | 115 km/h /5-20 min | |
| Electrification | 25 kV ac, 50 Hz | |