ABSTRACT

Caltrain operates a commuter rail service on the San Francisco Peninsula, serving approximately 37,000 people per day. The current diesel-hauled service of 98 trains/day consistently posts on-time performance of over 90% as it serves a distributed ridership demand between San Francisco and Gilroy. Rail service during peak periods combines express and limited stop trains operating five per hour, over a primarily double track system with several four-track segments and frequent interlockings. The rail line is also characterized by 25 passenger stations and 60 grade crossings.

In order to accommodate future growth in operation, the most heavily traveled 51 mile portion of this system between San Francisco and Tamien is scheduled to be electrified by 2014. The design for the electrification system has been progressing for several years and has now reached the 35% milestone. During the conceptual and preliminary engineering phases, it was determined that a 2 x 25 kV autotransformer type system would be the most appropriate for Caltrain's operations. A configuration with two main 115-2 x 25 kV main substations, 7 paralleling stations, and one switching station was developed to power the 8 car bi-level trains envisaged to be running on the line at five minute headways.

This paper will discuss certain aspects of the electrification design that are uniquely tailored to the Caltrain operations. Due to the relatively high frequency of train service, the capability of the electrification system to quickly and reliably remove (isolate) a section of catenary from service between interlockings to expedite the re-routing of trains will be of significant value. The
The benefits of using the system-wide fiber optic communications system in conjunction with motor-operated disconnect switches located at each interlocking to provide the necessary electrical isolation will be described. The use of the supervisory control and data acquisition (SCADA) system in conjunction with current sensors mounted on the motor-operated disconnect switches to expedite the location and isolation of catenary short circuits will also be examined. Through applications of advanced technologies from these areas, the components from several parts of the electrification system will be used to minimize operational disturbances, provide flexibility, and ensure safety in the dense suburban corridor.

**INTRODUCTION**

Traction electrification systems for modern passenger railways are comprised of the electrical equipment needed to power the railway rolling stock. This equipment includes the catenary system from which the pantograph-equipped rolling stock obtains power, and the substations that provide power to the catenary system. The voltage supplied to the rolling stock by modern main line passenger railway traction electrification systems (TES) is 25 kV.

The catenary system, often referred to as the OCS (overhead contact system), is divided into electrical segments, or “sections”. The electrical sections are further subdivided into elemental electrical sections.

- Electrical sections span from the substation to the end of the feeding section.
- Elemental electrical sections (EES) are the section of the OCS between consecutive catenary disconnect switches.

The manner in which these sections are configured is termed “sectionalizing”. The primary purpose of TES sectionalizing is to maintain normal train service, to the maximum extent
possible, by limiting the extent of an outage that may be caused by electrical short circuits ("faults") or maintenance work. Limiting the extent of an outage in this manner results in loss of traction power only to the faulted EES, thereby minimizing disruptions to train service.

Traction electrification systems by nature are typically subjected to frequent short circuits (faults) due to a number of factors that can include broken pantographs and catenary wires, wildlife contact, and tree contact. Faults can be of a permanent or temporary nature. Temporary faults, which are the most common, are typically caused by tree branch or wildlife contact. These can normally be cleared by automatic reclosing of the circuit breakers powering the affected section. Permanent (persistent) faults are typically caused by train pantograph failures, equipment failure and downed wires. These result in short circuits that cannot be cleared by circuit breaker reclosing operations.

A properly designed traction electrification system will minimize operational disturbances after a permanent fault. This design objective is particularly important for the Caltrain electrification since Caltrain operates a high density commuter rail type service. With an ultimate goal of five minute train service during peak periods, a prolonged power outage resulting from conventional fault location methods will have a potentially unacceptable delay on the train schedule. For this reason, Caltrain has been investigating economical ways to reduce the time to reliably locate and isolate permanent catenary faults, thereby enabling service to be quickly restored on adjacent tracks via the nearest interlockings.

**ATTRIBUTES OF THE CALTRAIN TES SYSTEM**

**Traction Electrification System**
Caltrain’s electrification will comprise a 50kV (2 x 25kV) autotransformer configuration. This type of system is commonly used for electrification of main line passenger railroads and provides for a traditional radial autotransformer type traction power system that is common to modern European and Asian railways and also Amtrak’s New Haven – Boston electrification.

The 51 miles of the Caltrain system which is to be electrified will have the following features:

- Two traction power (main) substations (TPS) with intake at 115kV from the local utility. The substations step down the supply voltage to 2 x 25kV for catenary and ‘negative’ feeder distribution to the OCS via two 60MVA transformers. These substations are the only source of traction power for the electrification and consequently provide power to all the tracks via electrical sections that extend between each substation to the switching station, and between each substation and the end of the line.

- One switching station (SWS) located at the midpoint between the two traction power substations. The switching station is located at the end of the radially fed electrical sections which are approximately 19 miles long. The switching station comprises of two paralleling stations connected back-to-back.

- Seven paralleling stations (PS) spaced 6-7 miles apart to provide voltage support and maintain the autotransformer electrical system. Each paralleling station comprises one 10MVA autotransformer, switchgear and OCS connections.

- Approximately 27 electrically switched interlockings. Typically there at least two interlockings between each traction power facility (TPS, PS or SWS). The catenary system at interlockings has section insulation installed providing the limits of the elemental electrical sections. OCS motor operated sectionalizing switches (MODs) are connected to switch across each section insulator in the catenary. Under normal operation OCS sectionalizing MODs are closed. These switches enable the de-
energizing of sections of catenary between adjacent interlockings for maintenance and repair. The insulation is located to permit trains to operate on sections of catenary adjacent to the section that is out of service. This is an important aspect of TES design, since train operations are dictated by the locations of interlockings, rather than the locations of substations.

- A permanent catenary fault will cause loss of power to all tracks in the affected TPS electrical section until the fault can be located and isolated.

- After a permanent fault, it will be imperative to isolate the fault to a single EES. An EES can be electrically isolated by opening the motor-operated disconnect switches at either end. This is the smallest section of catenary that can be electrically isolated within the larger TPS feed section.

**Supervisory Control and Data Acquisition (SCADA) System**

The SCADA system is the master system which monitors and enables the operation and control of the TES. It is comprised of the master station location at the Central Control Facility (CCF) and the remote equipment located in the field. The SCADA system will provide indication and control for all trackside facilities and equipment, as well as monitor and transmit real-time metering data, alarms, and events to the office end control system. The Caltrain SCADA system will transmit these functions via a fiber optic network to the CCF, where information storage and retrieval, alarm processing, incident and operations reports will be displayed for use by the power director (the system operator).

The SCADA System will include the following features:
- Duplicate or redundant communications interface, processors and power supply equipment at each traction power facility, trackside enclosure and the CCF.

- Automatic switch over to the secondary unit without loss of data in the event of failure of a unit or other contingency operation.

- Individually addressable processing equipment to provide continuous monitoring capability of all components on the system.

- Be based on an open system modular architecture which allows for expansion and reconfiguration of the system for future changes in technology, additional components or rail system configuration.

**Fiber Optic Backbone Communications Network**

A critical element of the TES, which must work seamlessly with the SCADA system, is the backbone communications network. It will function as the link to the traction power facilities, overhead contact system components, and signaling and grade crossing modifications along the route. As it provides the connections to this variety of new infrastructure, the communications system must provide a secure, redundant and highly reliable medium to carry data, voice and video to and from the CCF. It must also interface with and support existing and future equipment serving train operations, passenger information, IT, data and administration systems.

To serve the diverse needs of the Caltrain system and the future electrification infrastructure, a very secure and reliable communications network was sought. For speed, compatibility with the electrical environment, and expandability to support the present and future infrastructure, a fiber optic network was determined to be the most appropriate medium. Economic factors also
came into consideration when network configuration and installation methods were studied. After a comparison of technologies and research into the success of communication backbone configurations in the railroad environment, the installation of an aerial optical ground wire (OPGW) was chosen for Caltrain’s electrification.

The communications network will be configured with the following features:

- An optical ground wire (OPGW) will be attached to the catenary poles in place of a normal static wire. This combining of the electrical system’s requirement for a static wire and the communications system’s fiber cable into one cable has multiple benefits.
  - OPGW will be installed on both sides of the tracks to create a fiber ring (redundant path).
  - OPGW will be installed as part of the OCS installation for little additional labor costs (economical).

- A 96 single mode fiber core in each OPGW to provide capacity for point to point connections from field devices to network nodes as well as 100% spares.

- Two bi-directional fiber rings will be formed with a bandwidth of 10 Gb (OC-192) with 100 Mb access connections.

- Network nodes and access points distributed along the tracks at appropriate intervals to provide local fiber connection points to all traction power facilities, interlocking catenary disconnect switches, signal and grade crossing cabinets, stations and other devices.

- Protection against any single points of failure through a combination of redundant node connections for all TES devices and automatic data switching and rerouting in less than 50ms in the case of loss of the primary communications path.
TES FAULT LOCATION AND ISOLATION METHODS

OCS fault location and isolation for an autotransformer type traction electrification system involves the following two steps:

1. Determine the location of the fault relative to the nearest substation, and relative to the nearest sectionalized interlockings on either side of the fault (“location”);

2. Disconnect the section of OCS identified in step 1 above (the EES) from the rest of the power system (“isolation”).

There are a variety of methods employed by ac-electrified railways to locate and isolate permanent OCS faults. Several of these methods are briefly described below. For all of these methods, the descriptions below assume that the upstream substation circuit breakers have already opened and then successfully reclosed on the OCS for the unfaulted track(s). This operation leaves the OCS for the entire electrical section of the faulted track de-energized and “unparalleled”, since all paralleling station OCS circuit breakers in the electrical section are now open (paralleling station OCS breakers automatically trip when they sense a permanent loss of OCS line voltage). This “unparalleled” configuration is used for fault locating in traditional autotransformer type electrification systems. With the OCS completely isolated in this fashion, current will flow in only one direction when the affected substation OCS breaker is subsequently closed, greatly simplifying the fault location process. Less expensive “no load break” type motor-operated disconnect switches (MODs) can be employed for sectionalizing while the substation OCS breaker is open with this approach, since no current is flowing in the OCS during this time.
Manual Method

With this method, the electrification system operator, herein termed the “power director”, usually has no information about where the fault is located in the affected electrical section. This requires the power director to start opening MODs closest to the substation, sequentially working outwards, until the faulted section has been found. The power director first opens the MOD at the interlocking nearest to the substation on the faulted OCS, which typically takes on the order of 10 seconds, and then closes the faulted OCS circuit breaker. If the breaker automatically trips, then the fault is located between the substation and the nearest interlocking. If the breaker does not trip, the power director opens the breaker and the closed MOD, and closes the next MOD. This procedure is repeated until the fault has been located, after which the nearest MOD on the far side of the fault can be opened. After the faulted OCS elemental electrical section (EES) has been thus isolated, power can be restored to the unfaulted portion(s) of the electrical section, enabling operations to resume around the faulted EES. Each of these fault-finding cycles can take as long as 25 seconds to complete (10 seconds to open an MOD, 5 seconds to select and close the breaker and 10 seconds to close the MOD). With the large number of interlockings on the Caltrain system, the operational delays that could be encountered by this trial-and-error approach may not be acceptable.

Use of Substation Distance Relays to Calculate Distance to Fault

The modern microprocessor-based distance relays that are typically used to provide primary OCS protection in substations can calculate the total distance between the substation and the fault (1). This information would be communicated to the power director, who would use it to provide an indication of where to begin the manual fault location and isolation procedure described above. This approach has been used on the Amtrak Northend Project and UK West
Coast Mainline Railway (2). Reference (2) notes that typical distance calculation accuracy has historically been 10-15% for the cited railway applications, although some high impedance faults (about 5% of all faults) provide very inaccurate calculated distances. Some inaccuracy is inherent due to the complex nature of the mutual impedances involved; the impedance of the steel running rails also varies with current magnitude. This method is still a definite improvement over the manual method in terms of reducing permanent fault outage times, as noted in reference (2). However, the following points should be noted.

1. A 10-15% average measurement accuracy would translate into an error of between two and three miles for the longer Caltrain electrical sections, with all substations in service (approximately twice that distance with one substation out of service). With Caltrain’s frequent interlockings, this could result in the wrong EES being identified as the “first try” fault location by the power director.

2. A correct distance measurement either requires the OCS to be in the normal configuration, or else incorporate some way of keeping track of the system configuration (correlating OCS configuration changes with impedance changes as “seen” by the distance relays). This may be part of what is alluded to in reference (3) as being “difficult to implement in a privatized environment”.
Amtrak Northend Fault Location and Isolation System

A PLC-based fault location and isolation (FL&I) system was developed for the Amtrak Northend (New Haven to Boston) system for the purpose of locating and isolating faults during normal operating conditions; it is described in detail in reference (4). The Amtrak FL&I system, when enabled by the power director, determines the type of fault and its approximate location, based on information provided by the distance relays. It then proceeds to isolate the fault by automatically opening & closing the appropriate MODs and circuit breakers via the SCADA system. Ideally, the isolation sequence is performed within 30 seconds; if the FL&I system is not successful within 90 seconds, it “times out”, and the power director must assume control. The following points about Amtrak’s FL&I system should be noted:

1. The system can only operate when the TES is in the “normal” configuration (all traction power equipment in service).

2. It cannot locate faults in sections of OCS that are in parallel, such as yards and terminals, without the addition of automatic sectionalizing equipment.

3. The system must be maintained for it to remain functional. This includes updating the PLC database whenever the TES configuration or line impedances change. It is the authors’ understanding that Amtrak’s FL&I system is currently not being regularly used, primarily for this reason.

4. The interlockings on the Amtrak Northend are typically spaced much farther apart than the Caltrain system interlockings. This provides the distance relays on the Amtrak main substation OCS breakers with a greater acceptable tolerance for distance calculation error with respect to pinpointing fault location relative to interlocking location.

Application of OCS Sectionalizers at the Boston Terminal
The Boston Terminal is the northernmost end of the Amtrak Northend system. It is located approximately 2 miles north of the last paralleling station, and approximately 17 miles north of the last substation in Sharon, Massachusetts. Typical of electrified railway terminal facilities, the Terminal includes numerous parallel tracks and associated OCS. To improve fault location and isolation in the Terminal OCS network, several normally–closed “smart” pole-mounted circuit reclosers were installed to operate in conjunction with voltage and current sending devices, and open automatically to isolate faults before the Sharon Substation OCS breakers automatically reclose. These devices are 45 kV class, 250 kV BIL, single phase vacuum reclosers normally manufactured for North American utility usage, installed along with post insulator type current and voltage sensors, PLC control and SCADA network integration. When the sensors detect a high current combined with a loss of voltage (following protection operation at the supply substation), which signifies a downstream OCS fault, their associated vacuum recloser trips, isolating the fault. When two such reclosers are in series the downstream device is configured to inhibit the operation of the upstream device if both see the fault condition. The reclosers do not provide a “visible break” as would a MOD, since they use enclosed vacuum interrupters for switching.

Use of Frequent OCS Section Breaks with Distance Protection at Paralleling Stations

Some of the electrified commuter rail lines in Pennsylvania, New Jersey and New York employ an autotransformer type electrification system that differs in configuration from the Amtrak Northend type that is most commonly in service overseas. These lines include the Metro North New Haven Line, the NJ Transit Morris and Essex Line, and the SEPTA regional rail lines that formerly belonged to the Reading Railroad. Notable differences include the use of section gaps at each paralleling station, and the equipping of paralleling station OCS circuit breakers with
distance protection. This alternate configuration offers some reduction in the time required for fault location and isolation when compared to the time required for the traditional configuration, when no automation of the procedure is used. This reduction in time is attributed to the shorter feed sections and “distributed” system relay protection. However, this alternate configuration incurs considerable additional electrification system construction cost and substation real estate requirements. In addition, it does not by itself provide automatic fault location and isolation from interlocking to interlocking. Analysis of both configurations has determined that lower fault outage times can be obtained by using the lower cost traditional autotransformer system configuration if it is coupled with an FL&I system that works directly with the interlocking MODs. This approach to FL&I is presented below.

PROPOSED CALTRAIN TES FAULT LOCATION AND ISOLATION METHOD

Approach

Based on the authors’ prior knowledge of the Amtrak fault location and isolation scheme, Caltrain’s system configuration, and intimate knowledge of how 50kV autotransformer systems operate under fault conditions, a method of achieving the operating philosophy using available systems was investigated.

The challenges presented for any fault location scheme are to:

1. Accurately locate the fault;
2. Successfully select the faulted area (the EES);
3. Isolate only the affected EES;
4. Successfully reenergize the electrical section around the EES to permit the use of the nearest track crossovers (to the extent practically possible); and
5. Perform the above steps in the shortest time possible.

In order to accurately locate a fault, either a visual sighting or measurements are needed. Since visual sighting of traction power short circuits is not a reliable method on which to base system operations, system measurements are required to determine the fault location. An autotransformer scheme that does not rely on sectionalizing the OCS at paralleling stations will by its configuration react to a short circuit condition by tripping, or opening, the circuit breakers at the substation providing power to the entire electrical section. This occurs because the breakers providing power to each track in the electrical section will “see” the fault condition.

As a result of this condition, the OCS is de-energized and the paralleling stations disconnect themselves from the OCS. This provides for a radial feed when the substation automatically recloses the circuit breakers after a short time delay. A radial feeding configuration enables accurate measurement to be made in order to determine the location of a fault. The distance relays typically employed measure current and voltage at the substation. Based on these measurements and the system configuration, the electrical impedance of the faulted circuit can be calculated and an approximate distance away from the substation determined. With the measurement being made at the substation and the fault being some distance away, the possibility of error and the incorrect EES being selected is significant. Incorrect selection of the faulted EES can result in further breaker operations, which stress the circuit breakers and consume additional time.

Operation of the disconnect switches at either end of the selected EES would be by done via the SCADA system. Successful switch operation would instigate substation circuit breaker reclosure and re-energization of the remainder of the electrical section.
An understanding of the initial sequence of events of fault location and isolation is inherent to the system being designed for Caltrain. At the time of first reclosure, a scheme that can make measurements closer to the fault than at the substation, which may possibly be tens of miles away, will have a greater chance of first time success. As noted above, under radial feeding only the devices in the fault current path from the substation will “see” a current; the devices downstream of the fault will not. Consequently, by applying logic (SCADA system programming), the last device to “see” a fault current is closest to the fault. This process should remove the requirement for a second reclosure due to an incorrect EES selection because the measuring devices are located at the boundaries of each EES.

With the knowledge that the EES will be located between switches at interlockings, and that switching equipment and fiber optic-based communications will also be located at each interlocking, the obvious location to make field measurements of voltage and current for the purposes of fault location is at each interlocking.

In order to make the measurements, commercially-available sensing devices will be added to the conventional disconnect switches, and these measurements will be transmitted to the FL&I controller. In the same way that continuous measurements are often transmitted over SCADA systems, the measurements from theses devices are expected to be handled similarly. A traditional master/slave type of SCADA system only polls RTUs on a rotational basis, and this would normally be too slow for this application. However, with the fiber optic backbone being available, a high speed, reliable peer-to-peer type communications system can be a called upon to transport the current and voltage sensing device signals to the FL&I controller essentially instantaneously (to a resolution of several milliseconds). The use of modern, IEEE-recognized communications protocols that permit report-by-exception will enable these field devices to interrupt the polling process. This combined with the advent of addressable field devices which
Caltrain intends to adopt allows “as required” processing of the signals from all the sensing devices. System software programming, which could also monitor the system configuration at the time of a fault, can be used to determine which sensor inputs are applicable to the faulted electrical section, and to look at the signals from only these devices. Upon successful isolation of the fault, re-energization of the remainder of the electrical section by additional switching to fully close in around the isolated EES can be programmed to occur automatically, or by manual operation via the power director.

By applying the approach described, it is anticipated that all operational objectives can be met in the most efficient manner, and lowest initial and life-cycle cost. As with all similar systems, contingency operating configurations will add complexity, but it is believed that the system as described can accommodate the most common TES contingency scenarios through system software programming. The real-time status of all TES switching devices will be available to the FL&I system, allowing appropriate actions to be taken either automatically or by the power director.

For an example of the sequence of events when a fault occurs, refer to Figure 1.

**EQUIPMENT CONSIDERATIONS FOR THE PROPOSED METHOD**

The proposed FL&I system will use equipment components and concepts that have been proven in other power system applications, but, to the authors’ knowledge, have not yet been combined in this fashion.
Current and Voltage Sensors

The outdoor post insulator-type current and voltage sensors being proposed for this system are commercially available, and have been previously used for single phase railway application on the Amtrak Northend Project as noted above. The sensors for this application will provide continual measurements to the SCADA system via the systemwide fiber optic network. Lack of an output signal for a defined time interval will indicate sensor failure, enabling the status of the device to be known and alarmed upon failure. If a permanent OCS fault should occur while one of these sensors is out of service, adjacent sensors can be used to identify the fault location, in which case two adjacent EES will be removed from service. Programming logic can be incorporated into the SCADA system to “flag” sensors (and MODs) that are out of service, if desired, so that the SCADA system can still automatically determine which EES should be isolated when a fault occurs with a sensor (or MOD) that is out of service.

Combined voltage and current post insulator-type sensors with 1% accuracy are available for this 25 kV single phase application, as are separate voltage sensors. The combined sensor unit is being proposed for this project, since only one voltage reading is normally required for each EES (a second voltage sensor could be installed on the opposite side of each MOD for added security, but this embellishment is considered unnecessary). Voltage monitoring capability can be used to keep the power director informed of real time power status in each EES, to confirm successful MOD operation, or to monitor actual catenary voltage levels, all for minimal incremental cost.

Switching Devices
Standard no-load break motor operated disconnect switches are being proposed for this application. Since all MOD switching can be performed with the OCS de-energized, this is considered to be feasible. These MODs would be installed even if this FL&I automation system were not to be incorporated, so this approach enables the proposed FL&I system to be added at very low incremental cost. MOD operating times can be reduced from the quoted ten seconds to as low as six seconds by using a more powerful (faster) motor operator. If it is later determined that specific locations require even faster MOD operation, single phase outdoor vacuum switches that can also provide load break and even fault interrupting capability are available from at least one major railway electrification equipment supplier. These devices, proven for railway application, could also be used for yard sectionalizing applications similar to that described above for the Boston Terminal.

**SCADA System Interface**

The current and voltage sensors that will be installed on the interlocking MODs will require an interface with the SCADA system’s fiber optic communication network. At least one US manufacturer currently offers an off-the-shelf “pole-top RTU” designed to work with these sensors that includes the necessary high-speed analog-to-digital conversion. These devices will be interfaced to the SCADA system via an IEEE-approved peer-to-peer type communication protocol such as DNP 3.0 or IEC 61850 that supports report-by-exception data, enabling the “interruption” of the normal SCADA system field device polling process when an event such as a fault occurs. Use of these protocols will also enable the FL&I system “intelligence” to be distributed to a local (substation) level, while being supervised and maintained at the master station level.
SAFETY AND SECTIONALIZING

In addition to minimizing operational disturbances, the enhanced fault location ability of the proposed system also provides safety related advantages to clearing faults. Automatic fault location and isolation schemes are routinely designed to protect the electrification equipment and restore power to trains in the unaffected areas of the OCS for the benefit of the passengers on board. However, the advanced fault location and isolation design for the Caltrain electrification system will help protect the employees and the public to the next level. The primary feature of the system to accurately locate a fault without requiring multiple reclosures of the substation breakers will minimize the probability of restoring power to an area with a potentially dangerous condition. This will greatly reduce the chances of equipment damage, injury and loss of life. On a rail line with 60 grade crossings, 27 interlockings, and 25 passenger stations all within a span of 51 miles, the elimination of unnecessary restoration of power to areas where trees, people, and foreign objects could be in contact with or close proximity to the live equipment is an unquestionable safety benefit.

ADDITIONAL BENEFITS

As with many advances or unique applications of existing technology, the economics and complexities of pursuing the proposed system must be considered equally with the desire to deploy a new system. In this case the pursuit is worthwhile since there are several additional benefits of the Caltrain scheme relating to capital project costs, maintenance activities and provisions for the future expansion. These benefits include the following.

- The main components which enable the current sensing FL&I scheme to operate will be in place as part of the electrification system regardless. The MODs, the SCADA system
and the reliable, secure, high bandwidth communications network are necessary parts of the electrification infrastructure no matter what type of FL&I scheme is employed.

- The incremental cost and added complexity to the electrification system is very low. The current sensing devices and programming will add a very small percentage to the capital cost of the project.

- The substantial cost of circuit breakers and section breaks at all paralleling stations can be eliminated. The cost of this added equipment, labor and maintenance expenses to achieve fault isolation in the smallest area possible can be avoided with the current sensing scheme.

- Maintenance concerns for the current sensors are very low. The sensors are non-oil filled insulating devices and therefore do not present the maintenance and environmental issues associated with oil filled devices. The sensors can be self-monitoring and will be alarmed to indicate their own health. This information can be displayed in the office control unit rather than requiring constant field checks.

- The Caltrain scheme can be easily modified to suit catenary system modifications, reconfigurations and extensions such as additions or relocations of interlockings, sidings or additional electrified territory. These changes will require only software modifications instead of costly and disruptive field work.

- Real estate needs and additional visual impacts (such as for additional circuit breakers or pole mounted switchgear) will be minimized with the use of current sensors.

**SUMMARY**
During the preliminary engineering phase of the Caltrain Electrification Project, several fault location and isolation methods which have been employed elsewhere were initially considered. Various system configurations using combinations of technology, devices and equipment, both simple and complex, were studied and assessed for their applicability to the Caltrain system. But none of the existing schemes adequately served the needs of Caltrain's future operations as well as matched the characteristics of the rail corridor. The prime goals of protecting the electrical system and minimizing the effects of faults on rail operations needed to be met. Equally, the complexity and cost of the FL&I system on a newly electrified corridor were also taken into consideration. Lastly, the safety of workers and the public on the densely populated suburban corridor with dozens of grade crossings and passenger stations, influenced the conceptual design.

Taking these factors into consideration led the design team to develop a unique fault current sensing FL&I solution for the Caltrain system. It will make use of standard electrification components such as MODs, SCADA and fiber optic communications as the basis for a more advanced analysis of fault data. The scheme provides a sophisticated solution to the problem of quickly locating and isolating faults to the smallest EES on a 2 x 25kV autotransformer type electrification system. It will perform this task through relatively conventional use of available technologies and components which will be integrated in a new way to address the specific aspects of the Caltrain project. While additional engineering and development work is still to be performed prior to the implementation of the system, the work to date has shown that the Project Team will be able to tailor the current sensing FL&I solution to be uniquely appropriate to the Caltrain Corridor.
REFERENCES


TABLES AND FIGURES

[Figure 1 to be included here]
**SEQUENCE OF EVENTS:**
1. **Fault occurs at location X**
2. Protection at substation trips circuit breakers A & B
3. Circuit breakers at paralleling stations (C, D, E, F) trip on loss of catenary voltage
4. System is now unparalleled ready for reclose onto a radial system

**SEQUENCE OF EVENTS:**
1. Substation recloses circuit breaker A after short time delay
2. Current flows to fault location X via catenary
3. Disconnect switches 1, 2, 4, 5 with sensors register fault current and send signal over communications system.
4. Disconnect switches 3, 6, 7, 8, 9 also with sensors do not register fault current.
5. SCADA or PLC software monitors signals from switches 1 through 9 and determines that the last switch in the radially fed section on track MT1 to see fault current is switch 5. Determines fault is between switches 5 and 6.
6. Command issued to open switches 5 and 6 on track MT1 (elemental section ES2-5)
7. Switches successfully opened and power restored automatically by reclosing circuit breaker A a second time, and paralleling station breakers.

**FIGURE 1 — EXAMPLE FAULT LOCATION AND ISOLATION SEQUENCE**