TCRP
REPORT 71

TRANSIT
COOPERATIVE
RESEARCH
PROGRAM

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Track-Related Research: Volume 1
Broken Rail Detection ■
Control of Wheel/Rail Friction ■
Wide-Gap Welding Techniques ■

A Compendium of Three Reports on Joint Track-Related Research with the Association of American Railroads/Transportation Technology Center, Inc.

TRANSPORTATION RESEARCH BOARD

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TRANSPORTATION RESEARCH BOARD — NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
WASHINGTON, D.C. — 2001

TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transportation Association (APTA), *Transportation 2000*, also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA, the National Academies, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended end users of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

TCRP REPORT 71

Project D-7 FY'99
ISSN 1073-4872
ISBN 0-309-06701-3
Library of Congress Control Number 2001-135523

Price $40.00

NOTICE

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The members of the technical advisory panel selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the National Research Council, the Transit Development Corporation, or the Federal Transit Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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TRANSIT COOPERATIVE RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

and can be ordered through the Internet at
http://www.national-academies.org/trb/bookstore

Printed in the United States of America

FOREWORD

By Staff
Transportation Research Board

This report includes the results of three research tasks carried out under TCRP Project D-7, *Joint Rail Transit-Related Research with the Association of American Railroads/Transportation Technology Center, Inc.:*

- *Alternative Broken Rail Technologies for Transit Applications*
- *Prototype Demonstration of Film Coating to Reduce Noise and Wear in the Transit Environment*
- *In-Track Rail Welding in Transit Tracks*

The report should be of interest to engineers responsible for design, construction, maintenance, and operation of rail transit systems.

Over the years, a number of track-related research problem statements have been submitted for consideration in the TCRP project-selection process. In many instances, the research requested has been similar to research currently being performed for the Federal Railroad Administration (FRA) and the freight railroads by the Association of American Railroads' (AAR) TRansportation Technology Center, Inc. (TTCI) in Pueblo, Colorado. Transit track, signal, and rail vehicle experts reviewed the research being conducted by TTCI. Based on this effort, several research topics were identified where TCRP funding could be used to take advantage of research currently being done at TTCI for the benefit of the transit industry. Final reports on three of these efforts are presented in this publication.

Alternative Broken Rail Technologies for Transit Applications (Broken Rail Detection)

Three different technologies for detection of broken rails in track were evaluated at the FRA's Transportation Technology Center (TTC) in Pueblo, Colorado, for ease of installation, operating reliability, and susceptibility to false and missed events. These technologies offer alternative methods to track circuits for detecting broken rails (i.e., they do not require track circuits that control conventional signal systems, train shunt, or insulated joints).

Fiber-optic (i.e., a fiber-optic strand bonded to the rail) and strain gage (i.e., strain gage measurement of longitudinal stress) technologies were selected from technologies that have prototypes being investigated for use in freight railroads. A third technology that measures return ground current behavior was specifically proposed for transit applications, but no prototype has been built for testing at this time.

Prototype Demonstration of Film Coating to Reduce Noise and Wear in the Transit Environment (Control of Wheel/Rail Friction)

A field demonstration was conducted on the Portland Tri-Met Yard lead in Gresham, Oregon. Data suggest that, although the reduction in friction was minimal, noise generated from top-of-rail-to-wheel-tread contact was reduced significantly immediately after application. However, the coating used here did not provide a sufficiently robust modification of the surface to affect all trains for an extended period.

Results of the study show that the coating alone was insufficient to reduce friction and noise for an extended period. The most significant noise reductions resulted from migrating lubrication, suggesting that a constant, reliable source of lubrication is needed. One or more properly located wayside lubricators or some type of onboard flange lubrication system could provide this.

In-Track Rail Welding in Transit (Wide-Gap Welding Techniques)

TTCI conducted a study of the current status of and possible improvements for in-track rail welding in U.S. transit tracks.

A field test of wide-gap thermite welds in transit tracks was conducted in cooperation with the Port Authority Transit Corporation (PATCO) to study the feasibility of reducing the cost and time of track occupancy in repairing of rail or rail weld defects. TTCI surveyed the current use of wide-gap thermite welding by U.S. and foreign transit and passenger railroads. All the test welds were in good service condition at the time of this report. Survey results show that wide-gap thermite welding technology is in use and its application is expected to increase.

A survey of North American transit operators found that thermite welds made in recent years have been performing well, although some old thermite welds tend to have problems. The survey also found that welds fail when and where large longitudinal and lateral forces occur.

TTCI also reviewed potential alternative welding processes for in-track rail welding and formulated a set of criteria for the selection of an alternative in-track welding process. The factors considered include cost per weld, total welding time, service performance, requirements for welder’s skills, equipment portability, rail consumption and rail/tie movement, flexibility for rail sections and railhead wear, and initial capital investments. A workshop was conducted to evaluate the potential welding processes.

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BROKEN RAIL DETECTION

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AUTHOR ACKNOWLEDGMENTS

The authors wish to acknowledge Richard Morgan and John Peters for their contributions to this report.

BROKEN RAIL DETECTION

SUMMARY

The work presented here is covered under Task Order No. 01, "Broken Rail Detection," of subcontract number "TCRP No. D-7 Joint Track-Related Research with the Association of American Railroads, Transportation Technology Center, Inc." The TCRP contract is funded under the National Academy of Sciences (NAS) program TCRP 3322-099.

Three different technologies for detection of broken rails in track were evaluated at the Federal Railroad Administration's Transportation Technology Center (TTC) in Pueblo, Colorado, for installation, operating reliability, and susceptibility to false and missed events. These technologies offer alternative methods over track circuits for detecting broken rails. Thus to operate, they do not require track circuits that control conventional signal systems, train shunt, or insulated joints.

The fiber-optic (a fiber-optic strand bonded to the rail) and strain gage technologies (strain gage measurement of longitudinal stress) were selected from technologies that have prototypes being investigated for use in freight railroads. A third technology that measures return ground current behavior was specifically proposed for transit applications, but no prototype has been built for testing at this time.

FIBER-OPTIC TECHNOLOGY

Evaluation of technical, installation, and operational limitations suggests that the fiber-optic technology may be best suited to very short, complex track sections that are difficult to insulate and contain multiple ground return paths. This technology is sensitive to cracks that have not completely fractured the rail, thus it offers the potential of early detection and warning of impending failures, such as cracked thermite welds. Installation and repair of the fiber bonded to the rail is still in the developmental stages and hinders the feasibility for application over long distances.

STRAIN GAGE TECHNOLOGY

The strain gage technology appears to be effective in detecting breaks in continuously welded rail territories, but suffers from reduced sensitivity if temporary or permanent bolted rail plugs are installed. Also, sensitivity is low for rails that may break but not separate, such as might occur when the rail is in compression. Repair of the

sensing system after a break occurs (and the rail is subsequently replaced or welded) is not required unless the sensor is damaged or removed in the process.

TRACTION RETURN CURRENT TECHNOLOGY

The ground return technology offers a low-cost system for detecting breaks over long distances, but may have difficulty in deciphering changes in traction return current within turnouts, guard rails, and other areas where alternative electrical paths exist. A prototype demonstration is suggested of the ground return broken rail detection concept for evaluation at a full-scale installation.

CHAPTER **1**

BACKGROUND AND OBJECTIVE

A joint, multiproject, track-related cooperative research program was initiated under funding by the Transit Cooperative Research Program (TCRP). The goal of this project was to adapt the research already being performed by the Transportation Technology Center, Inc. (TTCI) for the Federal Railroad Administration (FRA) and the freight railroads for use by the transit industry, thus leveraging the TCRP investment. The TCRP program is being carried out under the oversight of a task force formed by the TCRP Oversight and Project Selection Committee. One of the early actions of the task force was to select four topics to be covered under this program. These topics were as follows:

- Broken rail detection,
- Transit switch design,
- Rail welding techniques, and
- Control of wheel/rail friction.

Three technologies for broken rail detection were evaluated. One technology, a new rail-break detection system proposed by the Metropolitan Transportation Authority—New York City Transit (MTA-NYCT), was evaluated through a theoretical analysis. The proposed system is based on detecting the imbalance of the traction current return current in the running rails, caused by a broken rail, to trigger an alarm.

The fiber-optic (a fiber-optic strand bonded to the rail) and strain gage technologies (strain gage measurement of longitudinal stress) were selected from technologies that have prototypes being investigated for use in freight railroads. A third technology, which measures return ground current behavior, was specifically proposed for transit applications, but no prototype has been built for testing at this time.

Broken rail detection on freight railways has traditionally been provided as an adjunct to the primary objective of track circuits for train control purposes. The running rails are used for sending low voltage DC or AC current between designated “blocks” or distances. Train wheels entering a section will shunt or cause a short circuit between the rails, causing a drop or elimination of the low-voltage signal, which is interpreted by the signal system logic to control signals or other train control systems (e.g., block signals and grade-crossing warning devices). A broken rail is interpreted as a train (i.e., the break in continuity caused by a separation in the rail is interpreted the same as if a train were present). Thus, to the signal system, the warning provided to a train approaching the “block” or segment of track is the same as if there were a train present.

In some cases, the track circuit will not reliably detect a broken rail. The most common failures that are not detected are rails that do not separate (e.g., cracked welds) and breaks that occur over tie plates. The former situation can occur during hot weather or when the rail has not been properly destressed. In rare cases, when the track circuit voltage is adjusted too high, a break may be bridged by voltage traveling through contaminated ballast.

In certain areas of the track structure, specifically special track work (e.g., turnouts and turnout components, crossing frogs, and other track work in congested areas), the need to provide insulated joints for track circuits results in unsatisfactory ride quality and accelerated track maintenance. With the advent of new technologies for train control (Positive Train Control or PTC), the use of non-track-circuit-based systems is being investigated. This includes the use of global positioning technology, satellite communications, and other communications-based systems for train location detection and control. Implementation of such train control technologies could make track-circuit-based signals redundant. Given such redundancy and the likelihood of the eventual removal of track circuits used for controlling signals, alternative technologies for broken rail detection should be investigated.

Several alternative technologies for detection of broken rails have been proposed. Three are discussed here:

- Strain-gaged rails,
- Fiber-optic cable bonded to the rail, and
- Traction return current monitoring.

CHAPTER **2**

TECHNOLOGY DESCRIPTIONS

Of the proposed technologies, two (strain gage and fiber optics) have had prototypes installed at the FRA's Transportation Technology Center (TTC) in Pueblo, Colorado, for in-track evaluation. This includes performance on long-term reliability, false or missed detection, repair requirements, and overall operation. An assessment of the third proposal—traction return current evaluation—has also been conducted.

2.1 FIBER-OPTIC DETECTION TECHNOLOGY

The fiber-optic detection technology investigated uses a standard single-mode fiber-optic fiber attached to the rail with epoxy or tape under the head along the entire length of track segment. A light source of a wavelength of 1550 nanometers is applied at one end of the fiber and is received at the other end. The light at the receiving end is converted to an electrical signal, which is monitored by a computer system. If a rail break occurs, fiber will break, the light will be stopped from reaching the receiver, and an appropriate indication will alert the signal system. For demonstrations at TTC in Pueblo, Colorado, a 62.5-micron-diameter fiber was bonded to the rail using epoxy and a tape backing and a specially fabricated application cart, as Figures 1, 2a and 2b show.

Then, a self-contained device for light source, transmission, receiving, and signal interpretation has been built for demonstration testing. This unit, supplied by Photonix Technologies, is shown in Figures 3 and 4.

The output of this Phototonix unit controls two different sets of dry contact relays. One set is triggered by a major loss of the signal (e.g., complete light loss at the receiving end). Such a loss may occur if the fiber breaks completely and no light is visible by the receiver. The second set is triggered if a reduction in signal is detected (e.g., if a fiber is damaged but not broken, thus blocking some of the signal).

2.2 STRAIN GAGE DETECTION TECHNOLOGY

This technology, provided by Salient System, Inc., Dublin, Ohio, uses a number of strain gage sensors installed on the gage side of the rail at intervals of 100 to 200 ft. After installation of the strain gages, the system must be calibrated. If the application is on new rail, this can be done before rail is installed in track. If rail is already in place, it must be cut in several locations and allowed to relax, thus creating a zero stress state for calibration purposes. Under production revenue service applications, sensors can be installed at the welding plant or in track just before rail destressing activities. By placing the detection modules before rail installation, the need to cut rail for calibrating at a zero stress state is eliminated. Figure 5 shows a typical strain gage protective cover installed on a rail.

Each sensor location consists of a strain gage microwelded to the rail web. A protective cover containing the battery, signal conditioning, and transmission equipment is bolted to the rail web. Under production conditions, the strain gage and cover can be installed in less than 30 min by a two-person trained technician crew.

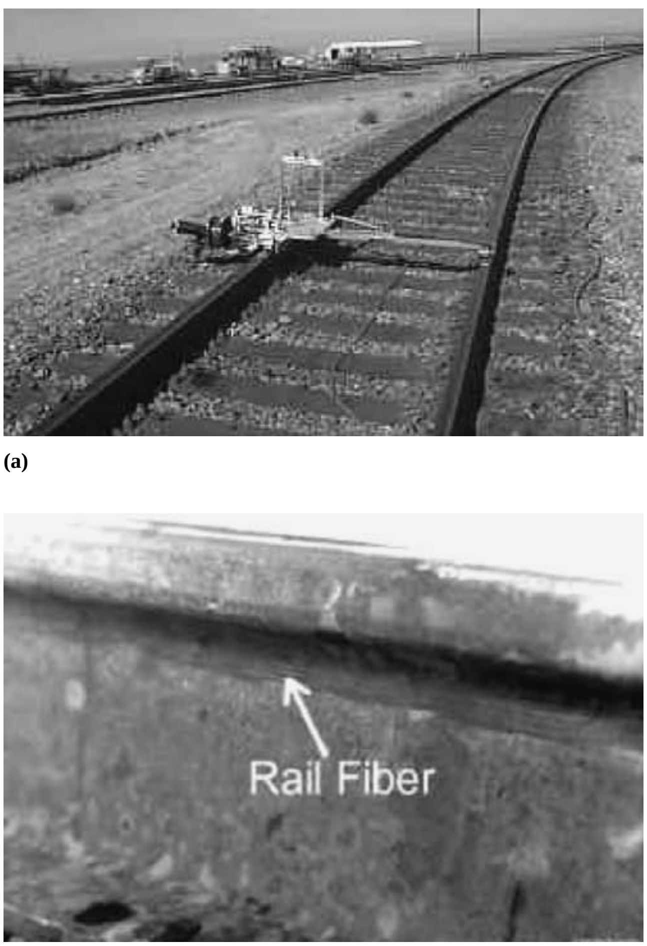
For the demonstration at TTC in Pueblo, Colorado, strain gage sensors were installed in a 5-deg. curve, as Figure 6 shows. Not shown is the base master station, which receives the signals transmitted from each of the sensors. For this test, the master station and antenna were located in a nearby signal bungalow. Periodically, the master station polls stress and temperature readings sent from each sensor. Through the use of proprietary analysis techniques, the stress and temperature variations at adjacent measurement locations are evaluated and compared. Certain combinations of stress and temperature can indicate a rail break, buckled track, or both. For the test installation at TTC in Pueblo, Colorado, the frequency of transmission was once every 10 min. The polling rate selected is based on what is projected as needed for freight railroad revenue service with a goal of obtaining a battery life of about 10 years. With such an installation, a rail break could occur and not be detected for up to 10 min. For transit applications, where train frequency is much higher, a very short or no delay is more appropriate. A more frequent transmission rate could result in reduced battery life, which could be addressed by alternative batteries or incorporating a replaceable unit in the sensor module.

2.3 TRACTION RETURN CURRENT BROKEN RAIL DETECTION

Electrified rail systems, whether they are powered through a third rail or an overhead catenary system, use the running rails as the basis for the traction current return circuit. The main objective of the design of the traction current return circuit is to keep the electrical losses (and, therefore, the voltage

Figure 1. Fiber-optic strand protected by epoxy and tape on the rail.

drop) to a minimum. The flow of the traction current through the return circuit to the electrical substations follows the path of "least resistance." In general, the running rails of multiple tracks are bonded together to form a multiple-branch electrical network to minimize the return circuit impedance and to reduce the tendency for stray current to flow in trackside structures.



(a)

(b)

Figure 2. (a) Fiber optic filament application system; (b) Fiber on the rail.

Figure 3. Front view of Photonix fiber-optic unit.

Figure 4. Back side of Photonix detection system, showing output relay control connections for major and minor trigger alarms and fiber-optic input and output ports.

Figure 5. Elements of the strain gage protective cover.

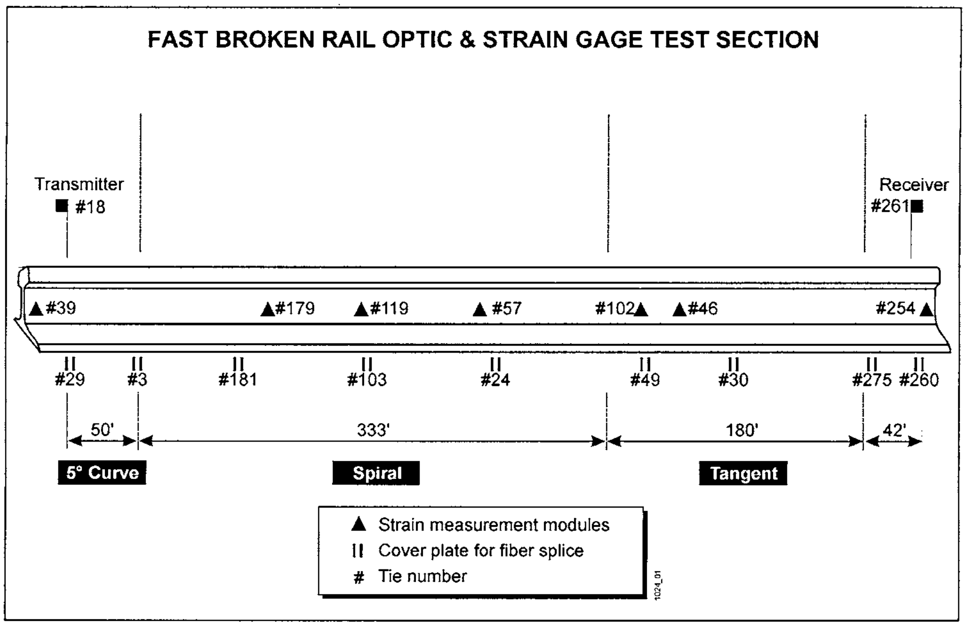


Figure 6. Strain gage and fiber-optic test zone detection system schematic.

The electrical bonding of running rails to form the traction current return circuit is carefully designed to ensure that ample current flows along and transfers among the various rail sections. Rail bonds are provided across rail joints to ensure longitudinal continuity. Frequent cross-bonds are provided between the running rails on a track and between adjacent tracks to provide parallel paths. On overhead catenary systems, frequent bonding is also provided from the running rails to the trackside support structures and the return conductor or static wire. By virtue of the interconnected network, all of the running rails normally carry traction return current, even from trains on adjacent tracks.

The effectiveness of the traction current return network has a major influence on the system design, because the length of the traction supply electrical section (the interval between adjacent substations) is based on the maximum allowable voltage drop to a train at the furthest point from a substation. In general, substations supply traction current in both directions from the center feed of adjacent substations. The maximum voltage drop occurs when the train is at the midpoint between substations. In AC overhead systems, under normal feed conditions, the electrical supplies to adjacent electrical sections are always isolated from one another because of electrical phase miss-match. In DC systems, adjacent electrical sections may either be connected or isolated, depending on the system loading and fault protection requirements.

The proposed MTA-NYCT rail break system uses the integrity of the traction current return circuit as its basis (*1*). The current flow in any one of the running rails can only be interrupted if either the rail or a rail joint bond is broken. In either case, an abnormal flow of current takes place in the adjacent rail cross-bonds to circumvent the discontinuity in the return circuit. If the resulting current imbalance can be reliably detected under all operating conditions, then the development of an alternative rail break monitoring system is possible. This system would depend on the presence of traction current flowing in the rail circuit. Two rail break detection configuration options, based on the traction current imbalance effect, have been proposed and both were analyzed as part of this task.

CHAPTER 3

BROKEN RAIL TECHNOLOGY EVALUATIONS

Both the strain gage and fiber-optic technologies were originally designed with freight railroad applications in mind. Some restrictions or impediments to implementation that may exist in the transit environment are discussed in this section. Only the strain gage and fiber-optic technology systems have been installed as working prototypes, thus only these two systems have actual field performance data on which to assess their limitations. The return current detection technology is a proposed concept and has been modeled only, thus limitations are based on engineering judgment.

The fiber-optic and strain gage systems were evaluated using prototype installations at TTC. Prior to 1998, the fiber-optic and strain gage systems had been demonstrated only in laboratories or on limited sections of track (*2*). Late in 1998, a 600-ft section of track on a 5-deg. curve was selected for a field demonstration of both systems (refer to Figure 6). This test section was selected because it was the site of a rail defect growth test, and the likelihood of a rail break (or thermite weld failure) was higher than at other locations at this test facility.

During the first half of 1999, several modifications and upgrades were made to both technologies; however, after mid-1999, several rail breaks occurred with varying degrees of detection success. Table 1 summarizes the most recent experiences of both systems. The fiber-optic system was deactivated because an acceptable repair method had not been developed after several rail breaks. The system was deactivated because of the high cost of repairing the fiber after broken rail repairs. Monitoring of both systems ceased after February 2, 2000, because of several missed detections caused by the temporary use of bolted rail plugs, rather than repair welds.

3.1 STRAIN GAGE TECHNOLOGY

The strain gage detection system is a proprietary device. It was evaluated as supplied by the vendor and no product development or improvements were attempted. The vendor installed strain gage modules and the receiving/monitoring system, with assistance provided by TTCI's track crew for rail destressing. The destressing operation was conducted after the strain gages were attached to the rail. During the test, no failures of the strain gage modules were noted, and the system properly interpreted broken rails from installation modifications made after June 1999 until approximately January 2000. TTCI provided a data logging computer, which monitored signal system function (track circuit), strain gage system output, and the fiber-optic detection system output.

During late December 1999 and into early 2000, several rail breaks occurred in rapid succession. The track crew was unable to keep up with the rail destressing and thermite welding was performed to maintain a continuous welded rail (CWR) section. After rail breaks occurred near (i.e., within 20 ft of) one or more strain gage module locations, the sensitivity of the system software was reduced. Several rail breaks occurred and were not detected for up to 12 hr after the failure, as Table 1 indicates. This was due, in part, to the rail being allowed to relax and run under the bolted joint condition of a temporary repair, which reduced system sensitivity to stress and temperature relationships. As long as CWR was maintained, the detection of a rail break occurred within the sensor array 10-min polling time. As stated by the vendor, a shorter polling time could be programmed into the sensors with a reduction in site-battery life.

Once a rail break occurred and the track was repaired, the strain gage system was immediately available for detection. The software was essentially self-calibrating by polling each sensor and establishing a new baseline where neutral temperature readings indicated a predetermined pattern. No field adjustments to sensor modules or receiving station software were required. Unless a sensor was damaged or removed during the failure repair process, no field adjustments were required.

Issues not evaluated during the demonstration include the possible effects of electromagnetic interference (EMI) and the operational environment on system performance. Track circuits and electrified traction systems were suspected as potential sources of EMI. Given that the Salient Systems' demonstration occurred on a section of non-electrified track, the potential noise sources were not directly evaluated. However, TTCI historically measures rail strain without difficulty on two electrified test loops, the Railroad Test Track (AC overhead catenary) and the Transit Test Track (DC third rail), both of which use active track circuits, including block signal, cab signaling, and grade crossing systems. Additionally, according to representatives of Salient Systems, their testing to date shows no interference from existing track and signal

TABLE 1 Summary of fiber-optic and strain gage broken rail detection history

DATE	EVENT	FIBER DETECTION	STRAIN DETECTION
12-08-98	Rail cut	YES	NO
03-26-99	Weld crack	YES (PM)	NO
03-29-99	Weld break	ALREADY	YES
09-08-99	Forced buckle	YES	YES
09-14-99	Rail cut/destress	YES	NO
10-03-99	Weld break	SYSTEM OFF	YES
11-10-99	Weld break	SYSTEM OFF	YES
12-08-99	Rail break	SYSTEM OFF	NO*
12-14-99	Rail break	SYSTEM OFF	NO
12-15-99	Rail break	SYSTEM OFF	NO**
01-24-00	Rail break	SYSTEM OFF	YES
01-26-00	Rail break	SYSTEM OFF	NO***
01-31-00	Rail break	SYSTEM OFF	NO***

*7-hr delay before system detected

**10-hr delay before system detected

***Nearby bolted joint

system circuits. Consequently, electrified traction systems and track circuits are not likely to present any serious EMI challenges to the strain-gage-based system.

Another potential issue not evaluated is the effect of EMI on the radio frequency (RF) link between the track module and the master station. Given that the link is a 900 MHz, spread spectrum link, its resistance to EMI is fairly robust as long as the RF noise floor is not too high. In urban environments where many consumer electronic devices (cordless telephones, for example) operate in the 900 MHz region, the potential exists for the signal density from these devices to raise the noise floor to levels that may affect the link's performance. However, because this effect was not directly evaluated during the demonstration, further investigation is needed.

3.1.1. Strain Gage Implementation Issues

Observations made after 14 months of monitoring a 600-ft length of track indicated that the strain gage technology successfully detected a number of broken rails, if the rail within 100 ft of the break remained continuously welded and no mechanical joints were installed.

The following observations reflect field test results:

- Advantages of strain gage technology:
  - –The detection system is ready for immediate use after a break is repaired.
  - –Buckled track can be detected without requiring extra sensors.
- Disadvantages of strain gage technology:
  - –10-min polling may be too long for transit headways; however, shorter polling intervals will require alternate battery power.
  - –Nearby mechanical joints desensitize the system; consequently, broken rails may be missed if mechanical joints are present nearby.
  - –Currently, installation of gages requires open or cut rail to obtain a "zero" stress for calibration. New techniques are being investigated to reduce or eliminate the need for cutting rail.

–Currently, master receiving stations can be no more than 2,000 ft apart. The distance between master receiving stations may be further limited because of radio links in tunnels and because of urban obstructions.

- Suitable environments in which to use strain gage technology:
  –In lengths of track where CWR is required.
  –Sensitivity in turnouts or over very short track segments is unknown.
- Unsuitable environments in which to use strain gage technology:
  –In jointed rail or if joints are allowed to remain in CWR (after defects) for any significant time, strain gage technology is inadvisable.
  –On existing track, where it is highly undesirable to cut the rail for obtaining a zero stress level, strain gage technology is undesirable.
  –On rail that is changed out frequently, the potential loss of strain gages, transmission boxes, and signal boxes attached to the rail makes strain gage technology impractical.

3.2 FIBER-OPTIC TECHNOLOGY

Fiber-optic filament can be very fragile and is easily broken if mishandled or bent; therefore, in the railroad environment, fiber-optic filament must be handled with extreme care during installation and repair efforts. An applicator cart and cleaning system have been fabricated that facilitate installation. The fiber-optic technology proved to be very reliable in detecting broken rails; however, most implementation drawbacks are related to installation and repair efforts.

For the fiber-optic filament to detect a crack or break, it must be rigidly bonded to the rail. For the bonding medium (i.e., epoxy, tape, or a combination of epoxy and tape) to remain attached, the rail surface must be dry and clean of rust, dirt, and oil. Ambient and rail temperature affected epoxy curing time and, in some cases, prevented the epoxy from reaching a hard cure. The optimum installation process allowed the fiber to be unrolled in a continuous filament and applied to the rail without any splices. Occasionally, an obstruction was encountered (e.g., rail joints, road crossings, turnouts, and crossing frogs), that required the fiber to be cut and a shorter jumper attached to bridge the complex rail section. This jumper was spliced at one or both ends, depending on the configuration of the obstruction. Often it was attached manually to the rail, thus requiring significant track occupancy time. Thermite or other welds that are configured with a large upset or collar were carefully cleaned and an epoxy type "ramp" built up on the rail to allow the fiber to follow a path without introducing a kink or sharp bend. When a weld or rail cracked in this area, the epoxy ramp also cracked or became dislodged, breaking the fiber and triggering a detection.

After a rail or weld broke, the fiber also needed to be repaired. In most cases, the bonding medium prevented the fiber from being removed intact, thus a splice connection could not be made at any random location. The fiber can be spliced where it is "free" and open; therefore, in railroad applications, a loop of fiber is incorporated into the initial installation at periodic distances for future access. Rail breaks occurring between loops required removal and reattachment of the fiber between the loops, with splices occurring at each end.

For these reasons, with the current state of application and repair techniques, the fiber-optic detection technology is not suited for lengthy sections of rail unless broken rail occurrences are expected to be very infrequent. The fiber-optic detection technology is suited to short lengths of rail that are difficult to insulate or where insulated joints are highly undesirable because of track maintenance and ride and noise quality issues. Such areas are encountered in turnouts, interlockings, and crossovers, where a large number of rails are located in a confined space. Fiber-optic detection zones could easily be set up to check various routes and components of turnouts (i.e., along rail bases, frogs crossings, and switch points) that are virtually impossible to protect with track circuits.

A feature of the fiber-optic detection was its ability, with additional hardware, to detect the distance a break is located from the light source.

A limitation of the fiber-optic technology, with the present application system design, was its proximity to the third rail for some transit operations. In the freight railroad environment, the gage side of the rail tends to be dirtier and greasier than the field side, thus the application system was configured to install fiber on the field side. This configuration allowed personnel to have easy access to the field side of the rail, along with access on the ballast shoulder for repairs and installation. To preserve equipment and safeguard personnel safety, the third rail should be de-energized for transit installations, and, in some cases, the existing prototype installation equipment will need to be redesigned for physical size conflicts.

3.2.1 Fiber-Optic Implementation Issues Based on Field Test Results

Observations made after 12 months of monitoring a 600-ft length of track indicated that the fiber-optic technology successfully detected a number of broken rails; however, fiber repair techniques were such that the system was not available for detection immediately after the rail was repaired. The following observations reflect field test results.

- Advantages of fiber-optic technology:
  –Detection of buckled track, without extra sensors, is possible.
  –Detection of weld cracks, before a full break occurs, is possible.
  –Application is promising over very short distances that are difficult to insulate.

- Disadvantages of fiber-optic technology:
  - –Rail surface must be clean and dry before fiber can be attached.
  - –Epoxy set up time may take too long during cold weather.
  - –Mechanical joints require jumpers or splices, which can reduce signal strength and limit the length of the detection zone.
  - –Fiber-optic filament may debond at large obstructions on the rail (e.g., at sections with roughly finished thermite welds).
  - –Sharp bends around thermite welds must be avoided.
  - –Special care must be used when handling fiber materials.
- Suitable environments in which to use fiber-optic technology:
  - –In difficult to insulate track sections or track sections where insulated joints are rare, fiber-optic technology is desirable.
  - –In short sections of track (i.e., less than 3,000 ft), fiber-optic technology is applicable.
  - –At labor-intensive sites (i.e., over 3,000 ft), fiber-optic technology may be warranted.
- Unsuitable environments in which to use fiber-optic technology:
  - –On rail with a significant number of joints, use of this technology is problematic.
  - –On rail that is changed out frequently, the loss of fiber material attached to the rail makes this technology unsuitable.

3.3 TRACTION RETURN CURRENT DETECTION TECHNOLOGY

Evaluation of this technology was based on assessing the concept and predicting performances using a model to simulate various conditions. Two variations of the return current detection concept were evaluated: a measuring cross-bond differential technique, and a center feed shunt current measuring technique. Both techniques are described thoroughly in Appendix A to this subreport.

Both concepts can only detect a broken rail that occurs between a train and the substation location. Broken rails that occur when no train is present or when a train is approaching may result in a very short notification time. The application of a load resistor that periodically simulates a train in the block might suffice for such situations. Such an application would require additional control software for interpretation. Simulation data indicate that a coasting train will still produce sufficient return current to allow broken rails to be detected; however, this has not been verified.

The placement of special track work (e.g., crossing frogs and turnouts) or changes in the environment because of freezing rain, snow, and other causes of ground faults may result in false or missed detections. Areas where guard or restraining rails are bolted or attached to the running rail may mask detection of broken rails. This will depend on the amount of return current that flows around a break and through the guard rail, then back to the running rail. This is a limitation of most existing track circuits as well. The influence of such conditions on detection sensitivity cannot be fully explored with the model as it currently exists. When trains are not present or are not moving, broken rail detection may still be possible, depending on other traction return currents. A limited field prototype demonstration is required to fully evaluate such conditions.

Many of these limitations are theoretical in nature. It is anticipated that using advanced data processing and evaluation techniques (including various pattern recognition and learning software such as neural network techniques) can successfully address most of these anomalies.

CHAPTER **4**

SUMMARY OF PERFORMANCE ISSUES FOR EACH TECHNOLOGY

Table 2 lists the ratings of various performance issues for each technology tested. The high or low rating relates to each parameter; thus, a high or low rating is not always an indicator of a good or bad rating by itself.

TABLE 2 Performance rating table

	Detection Technology Rating		
Performance Issue	**Strain Gage**	**Fiber Optic**	**Return Current**
Systemwide application	Low	Low	High
Ease of installation	Medium	Low	High
Ease of repair after break	High	Low	High
Application at mechanical and insulated joints	High	Low	High
Ease of application at turnouts, special track work	Low/Unknown	Low	High
Detection sensitivity at turnouts, special track work	Low/Unknown	High	Unknown
Detection sensitivity at joints, mechanical joints	Low	High	High
Ease of application around third rail clearances	Medium	Low	High
Hardened against damage during track maintenance	Low	Medium	High
System reliability; i.e., false alarms	Low (Except if bolted joint is installed nearby, then high)	Low (Except if fiber damaged, then high)	Low
System reliability; i.e., missed breaks	Medium (Low reliability if rail in compression)	High	High
Ease of interface to signal or train warning system	High	High	High
Ability to use existing level of maintenance skills	Medium	Low	High

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Each of the three technologies offers specific advantages and disadvantages, but the return current monitoring technology appears to offer the widest application for long distances in transit applications.

For very short distances, in complex track work, the fiber-optic technology offers the most flexibility and sensitivity. For distances longer than 3,000 ft, it currently is not practical to use fiber-optics. With improved application technology, however, distances over a mile could become practical.

The strain gage technology has shown excellent performance in CWR sections where repair welds can be installed immediately after a rail break is removed. Prototype versions of the fiber-optic and strain gage systems have been demonstrated and a field demonstration could easily be initiated. The simultaneous use of two technologies (one for complex track work and another for open track) is not the most cost-effective solution, but may be required to adequately detect broken rails in all areas. The constraints examined here are primarily the result of the physical locations specified in a freight railroad environment; thus, applications specifically tailored to transit may reduce or eliminate these concerns. All technologies could interface with an existing signal system or be configured to provide rail status information to communications-based train control systems.

No operating prototype of the return current monitoring technology has been fabricated for transit use. However, most components could be available either off the shelf or with very little modification. It is suggested that a candidate site be selected and a demonstration of this technology be conducted by an appropriate organization. A revenue service operation could incorporate a return current monitoring system operating in tandem with an existing track circuit-based system. A separate data recording device could log all "real" events detected by the existing track circuit system, while also recording alarms detected by the return current system. This demonstration could also be conducted on a non-revenue track at TTC, with electrical shunts acting to simulate actual trains. In either the TTC or the revenue service case, broken rails could be simulated by opening of rail joints or cutting rail to determine system sensitivity.

REFERENCES

1. Association of American Railroads, “Expanded Workshop on Rail Defect and Broken Rail Detection,” Pueblo, Colorado, July 1997.
2. Schroeder, M.P. and Reiff, R.P., “Evaluation of Fiber-Optic Method for Detecting Buckled or Broken Rail,” RS-99-003, Association of American Railroads, Pueblo, Colorado, February 1999.

APPENDIX A

EVALUATION OF THE MTA-NYCT BROKEN RAIL DETECTION SYSTEM

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CONTENTS

A1 BACKGROUND

In the past, broken rail detection has been integrated into the track signaling system. The track circuits designed to detect the presence of a train in a signaling block can also be used to detect a broken rail. However, with the advent of new, communications-based, train control systems, such as Positive Train Separation (PTS), the conventional fixed-block track circuits are being eliminated. Thus, other methods of rail break detection are required to ensure the integrity of the track.

The evaluation of a track circuit-less rail break detection system, proposed by MTA-NYCT, was described in a paper presented at a railroad industry workshop in 1997 and is based on detecting the changes in the traction return current flow caused by a broken rail (*1*, pp. 465–473).

A2 SYSTEM DESCRIPTION

A2.1 The Traction Current Return Circuit

Electrified rail systems, whether they are powered through a third rail or an overhead catenary system, use the running rails as the basis for traction current return circuit. The main objective of the design of the traction current return circuit is to keep the electrical losses (and, therefore, the voltage drop) to a minimum. The flow of the traction current through the return circuit to the electrical substations follows the path of "least resistance." In general, the running rails of multiple tracks are bonded to form a multiple-branch electrical network to minimize the return circuit impedance and to reduce the tendency for stray current to flow into trackside structures.

The electrical bonding of the running rails to form the traction current return circuit is carefully designed for ample current and transfer among the various rail sections. Rail bonds are provided across rail joints to ensure longitudinal continuity. Frequent cross-bonds are provided between the running rails on a track and between adjacent tracks to provide parallel paths. On overhead catenary systems, frequent bonding is also provided from the running rails to the trackside support structures and the return conductor or static wire. By virtue of the interconnected network, all of the running rails normally carry traction return current, even from trains on adjacent tracks.

The effectiveness of the traction current return network has a major influence on the system design, because the length of the traction supply electrical section (the interval between adjacent substations) is based on the maximum allowable voltage drop to a train at the farthest point from a substation. In general, substations are located to supply traction current in both directions toward the center point between adjacent substations. Maximum voltage drop occurs when the train is at the mid-point between substations. In AC overhead systems, under normal feed conditions, the electrical supplies to adjacent electrical sections are always isolated from one another because of electrical phase miss-match. In DC systems, adjacent electrical sections may be connected or isolated from each other, depending on the system loading and fault-protection requirements.

A2.2 Proposed MTA-NYCT Rail Break System

The proposed MTA-NYCT rail break system uses the integrity of the traction current return circuit as its basis. The current flow in any one of the running rails can only be interrupted if either the rail or a rail-joint bond is broken. In either case, an abnormal flow of current takes place in the adjacent rail cross-bonds to circumvent the discontinuity in the return circuit. If the resulting current imbalance can be reliably detected under all operating conditions, then the development of an alternative rail break monitoring system is possible. However, this system would be dependent on the presence of traction current flowing in the rail circuit. Two rail break detection configuration options, based on the traction current imbalance effect, have been proposed (*1*, pp. 469 and 471). Both were analyzed as part of this task.

A2.2.1 Cross-Bond Current Difference Detection Method

The Cross-Bond Current Difference Detection Method is depicted in Figures A1 and A2. In this concept, current detectors are installed at each cross-bond location to measure the differential current flowing from the two rails into the cross-bond. Based on the reference literature, the typical distance between cross-bonds on the New York transit system is approximately 2,000 ft. Under normal conditions, the traction current flows from the wheels of the train power cars to the running rails on which the train is situated. Then the traction current is distributed equally among all of the running rails that are linked by the nearest cross-bonds, then along all of the rails in parallel toward the substation. At the substation, the traction current is diverted into the cross-bond and transferred to the negative feeder.

Figure A1 represents a section of two parallel tracks, extending from a substation connection on the left (at cross-bond A) for approximately 5,000 ft. Intermediate cross-bonds (B and C), spaced at 2,000-ft intervals, are also shown. A train, conducting a traction return current into the two running rails, is assumed to be in the lower track, to the right of cross-bond C. For the purpose of this illustration, contact between the wheels and the rails is assumed good, the track structure is well insulated from the ground, and no track-side return current conductors are used. Under these circumstances, the traction current flows toward cross-bond C, where it is distributed equally among all four rails. Depending on where the train is located with respect to the next cross-bond (cross-bond D, not shown on the diagram), a proportion of the current is also distributed into the parallel running rails by that

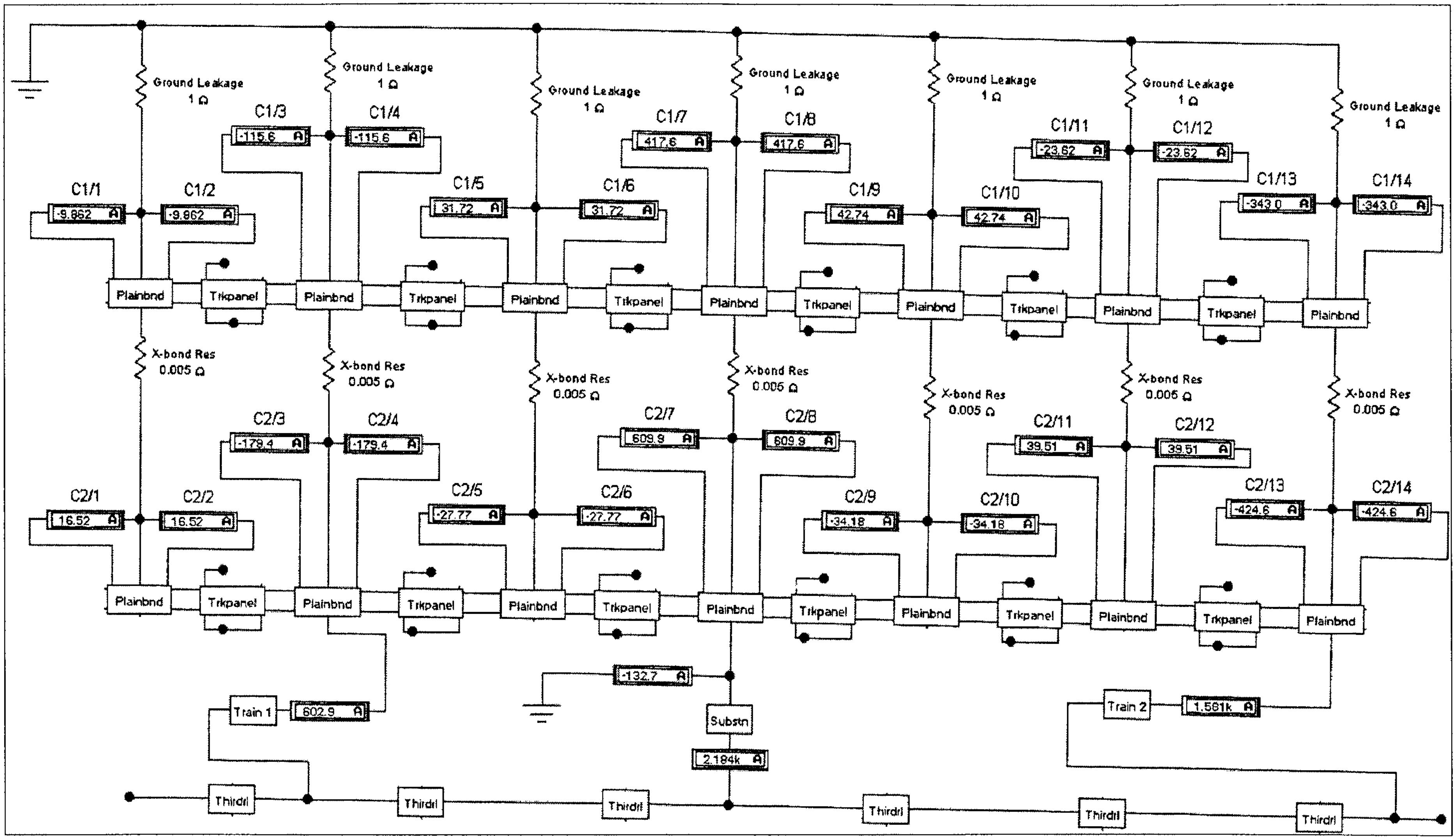

Figure A1. Current difference method, center substation, two trains, no rail break.

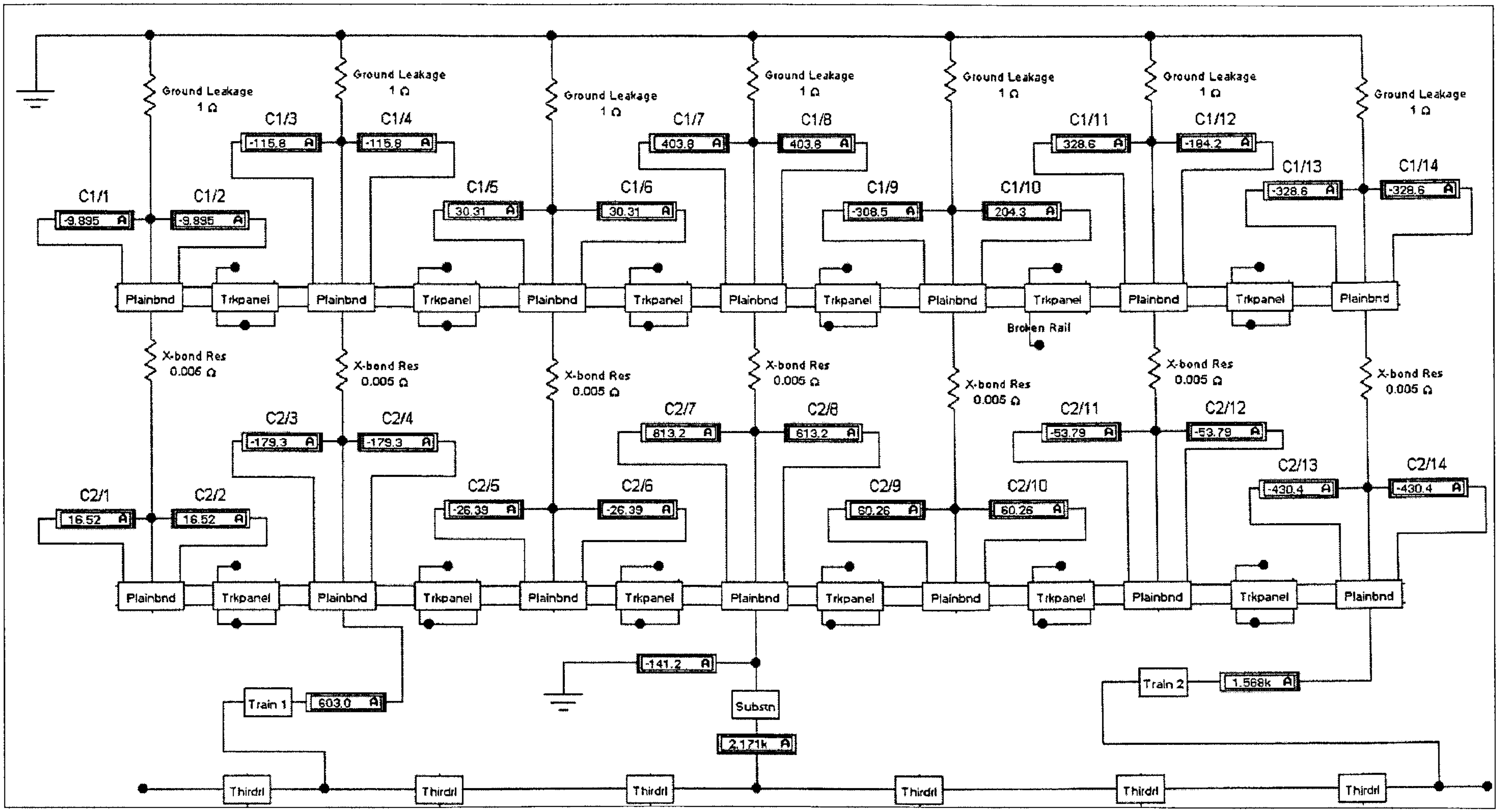

Figure A2. Current difference method, center substation, two trains, one rail break.

cross-bond. At cross-bond B, assuming that the electrical resistance characteristics of all four running rails are identical, there is no significant transfer of current through the cross-bond. At cross-bond A, the four components of the traction return current are recombined to flow into the substation negative feeder. Under ideal conditions, described here, the flow of current from the cross-bonds to the rails is balanced, with no differential between the left and right rails.

Under the broken rail scenario depicted in Figure A2, current is forced to flow around the discontinuity in the traction current return circuit caused by the break in the rail. Under this condition, the current is forced to flow from the broken rail, through cross-bond B to the adjacent track and through the rail-to-rail bond to the good rail on the same track. This results in an unbalanced current flow at the broken rail end of cross-bond B. Similarly, the current flow from the broken rail end of cross-bond A is also unbalanced. Reliable detection of this current imbalance could indeed be used to indicate a broken rail condition. Furthermore, the protection is provided to all of the tracks in the traction current return circuit network.

A2.2.2 Detector Current Shunt Method

Figures A3 and A4 depict the detector current shunt method, also referred to as the center shunt method. In this method, the same basic rail and multiple track cross-bonding scheme is assumed. But instead of using current difference detectors on the rail connections, a separate detector bond is used. This consists of an additional rail-to-rail bond on each track, without the cross-bond connection, located approximately at the mid-point between cross-bonds. A simple shunt is then used to monitor the current in the detector bond.

Under normal rail conditions (Figure A3), the cross-bonds distribute the traction return current to each of the parallel rails in the network. Consequently, the rail-to-rail voltage difference is small and no significant current flows in the detector bond. However, there may be some transient current transfer as the train passes over the section.

Under a broken rail condition (Figure A4), the detector bond adjacent to the break and the cross-bond on the other side of the break (cross-bond B in case shown) serve to divert the traction return current around the discontinuity. This causes an unbalanced current flow in cross-bond B and a measurable current to flow in the detector bond. Again, reliable detection of the center bond current would serve to provide broken rail protection and coverage for all the tracks in the network.

A2.2.3 Broken Rail Detection System

Either of the two unbalanced current flow effects could be used to form the basis of a broken rail detection system. In either case, the measured current effect would be compared against a threshold level. A measurement exceeding the threshold would be used to trigger an alarm to stop trains from operating over the suspect track. The hope expressed by the author of the MTA-NYCT paper was for a simple, standalone system (*1*, p. 468). Based on the complexity of a typical transit track layout, a simple system may not be possible. More complex analysis techniques may be necessary to ensure that false alarms are prevented.

A2.3 Preliminary Design Review

Preliminary review of the MTA-NYCT design information confirms that the operational logic of both options is valid. Based on the limited test data presented in the reference paper, a broken rail appears to give a current imbalance of significant magnitude to make either system capable of indicating a broken rail condition (*1*, p. 471). However, for this rail break detection system to be successful, local track features and environmental conditions must be considered. For example, a system that will only operate when the track is dry or in locations where there is no guard rail would not be a practical proposition for a transit application. Two of the key issues affecting the reliability with which a measurement of the change in traction current distribution can be used to detect a broken rail are (1) the magnitude of the change being measured and (2) the time duration available to measure and process the data. A model simulation study was carried out to address these issues.

A3 MODELING THE SYSTEM

The purpose of the modeling study was to answer the following three basic questions regarding the two proposed systems:

- Do the basic traction current return network parameters systematically change in response to a broken rail?
- What are the characteristics of the network response in relation to the passage of trains (e.g., time constants, trains on adjacent tracks, loaded or empty trains)?
- What is the likely effect of external factors (e.g., contaminated or grounded rails) on system reliability?

Subsections A3.1 through A3.4 describe the tools and methodology used to provide the answers to these questions.

A3.1 Modeling Tools

The software used for this study was a commercially available electronics/electrical simulation package, Electronics Workbench® EDA, Version 5.0c. This product, which is marketed by Interactive Image Technologies Ltd., is based on the "SPICE" simulation engine, developed by the University of

California at Berkeley. The advantage of using a package like Electronics Workbench® EDA is that it contains a library of standard components that can be readily configured into a customized electrical network. For repetitive blocks of circuitry, customized subcircuits can be a collection of assigned names. The combination of the standard library components and customized subcircuits makes the task of building and modifying the model a simple undertaking, providing the system parameters are readily available.

A3.2 Methodology Overview

Since the modeling was designed to study the behavior of a DC-powered, third rail, distribution system, the model was limited to a simple resistor network. From the data provided in the reference paper, any system based on traction return current imbalance would be a quasi-static process (*1,* p. 469). Consequently, the modeling was limited to steady-state analysis. The simulations were also performed using constant train power loading. However, the model was set up to enable the train power level to be selected for each run, and a range of power settings was used as part of a sensitivity analysis.

A3.3 Development of the Basic Model Modules

Figure A5 shows the basic network used for the simulations. Extensive use was made of the Electronics Workbench® EDA customized subcircuit capability in developing this network. The network shown in Figure A5 represents the traction current return circuit formed by a section of two-track railroad, approximately 12,000 ft long. The simulated track segment is divided into six equal lengths (approximately 2,000 ft long), each separated by a track rail-to-rail bond and an inter-track cross-bond. Two basic subcircuits were created to represent the track segment: "Trkpanel" and "Plainbnd." The three subcircuits, named "Substn," "Thirdrl," and "Train #" were created to represent the substation, a segment of third rail, and the load due to a train, respectively. The example shown in Figure A5 is configured with the substation in the center of the 12,000-ft track section. In this example, "train" loads are shown at either end of the track segment. For the purpose of this simulation exercise, the substation spacing on the "system" is assumed to be 12,000 ft.

Details of each of the subcircuits are shown in Figure A6. The Trkpanel subcircuit consists of a four-resistor network, each with a resistance of 0.02 ohms, which is the resistance of a 1,000-ft length of rail. (*2,* Ch. 23, Sec. 91, paragraph 216). External connections are provided on the left and right sides to connect the rail resistance segments in series. External connections are provided at the top to complete a mid-section rail-to-rail bond, if necessary, and at the bottom to introduce a rail break. The Trkpanel subcircuit is also a convenient location to connect a simulated "train" into the system.

The Plainbnd subcircuit has no electrical components, only through-connections to external terminals. External connections are provided on the left and right sides to provide continuity when the subcircuit is connected in series with the Trkpanel element. External connections are provided at the top for the configuration of the connections of the "running rails" into the cross-bonds. It is also an alternative location for connecting the "train" into the system.

The power supply and distribution system for the model comprises the Substn and Thirdrl subcircuits. The Substn subcircuit consists of a simple DC power supply (shown as a battery) set at an output voltage of 600 V. No attempt has been made to represent a real transit rectifier substation with voltage regulation, since the purpose of this study was to determine the characteristics of the rail traction current return circuit under the various load conditions. The "Thirdrl" subcircuit contains two resistors (0.008 ohms) in series, each representing a 1,000-ft length of two parallel sections of third-rail conductor. External connections are provided at the top and the bottom to allow for the connection of a substation or a "train" load onto the third rail.

The "Train 1" and "Train 2" subcircuits are identical in basic components and are designed to simulate the loading due to a train. Each subcircuit consists of three fixed resistors and one potentiometer. The potentiometer can be adjusted to set a load level ranging from full power (equivalent to 1.2 MW) to idle power (150 kW). Two versions of the same subcircuit were made available so that two trains with different power settings could be simulated on the network at the same time, if necessary.

Finally, the Electronics Workbench® EDA software has the capability to nest subcircuits within subcircuits. Using this capability, another subcircuit, "Tracksec," was created, containing the components necessary to represent one complete 12,000-ft segment of a third rail and track network. External connections were included to enable several of the segments to be connected in a series chain and connect "train loads" into the system where necessary. This enabled the modeling effort to include "end effects" due to adjacent electrical sections.

A3.4 Model Configuration

Configuration of the basic model network (Figure A5) was necessary to represent each case of the two rail break detection methods under review.

A3.4.1 Current Difference Method

Figure A1 is the basic network used to represent the Current Difference Method. The example shown in Figure A1 represents two trains on the same two-track segment, supplied by a central substation. Bonds have been installed on the lower terminals of the Trkpanel subcircuits to link the rail segment together (no broken rails). Ammeters have been connected between the cross-bond terminal and the "left"

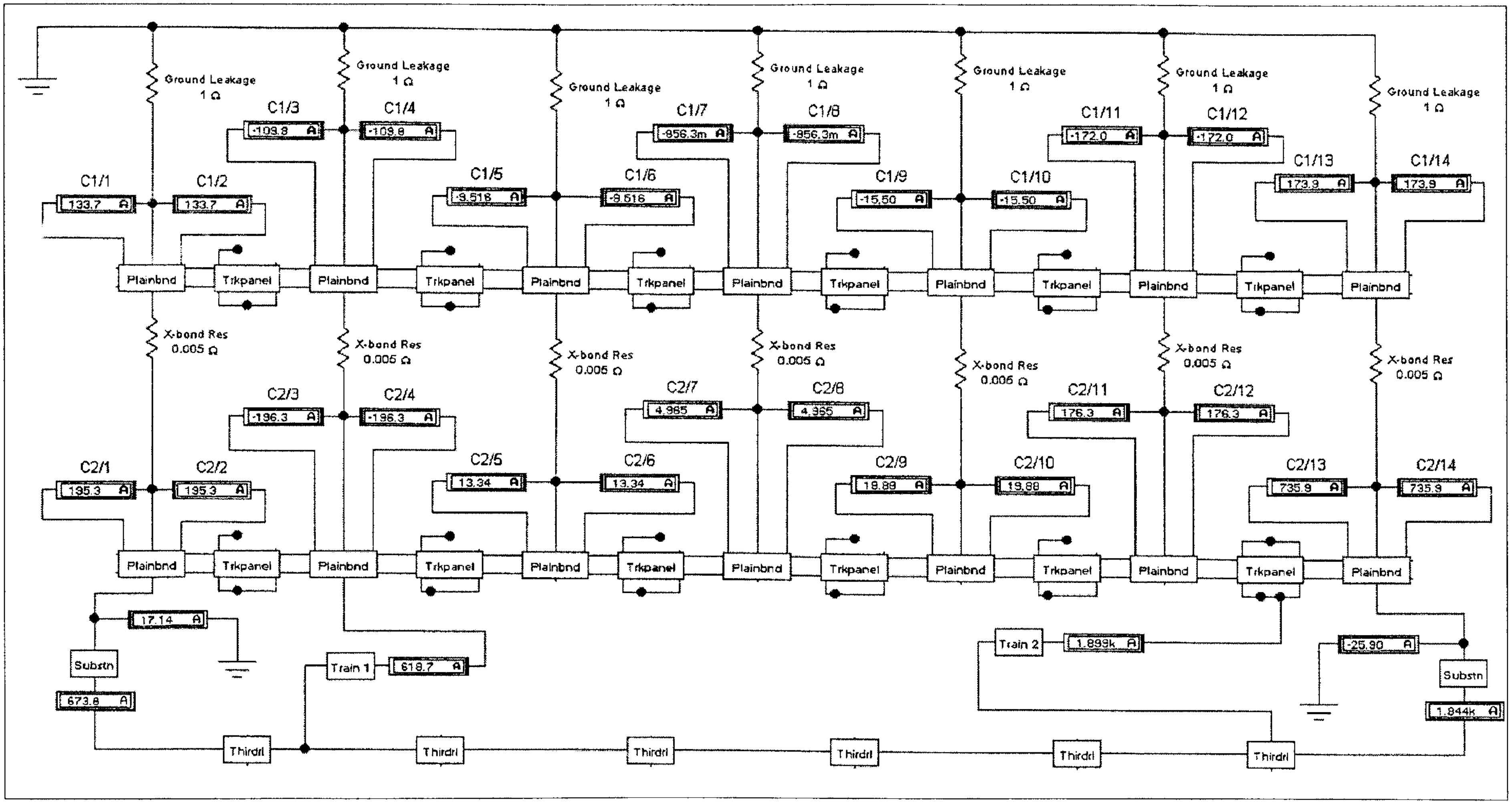

Figure A-3. Current difference method, two interconnected substations, two trains, no rail break.

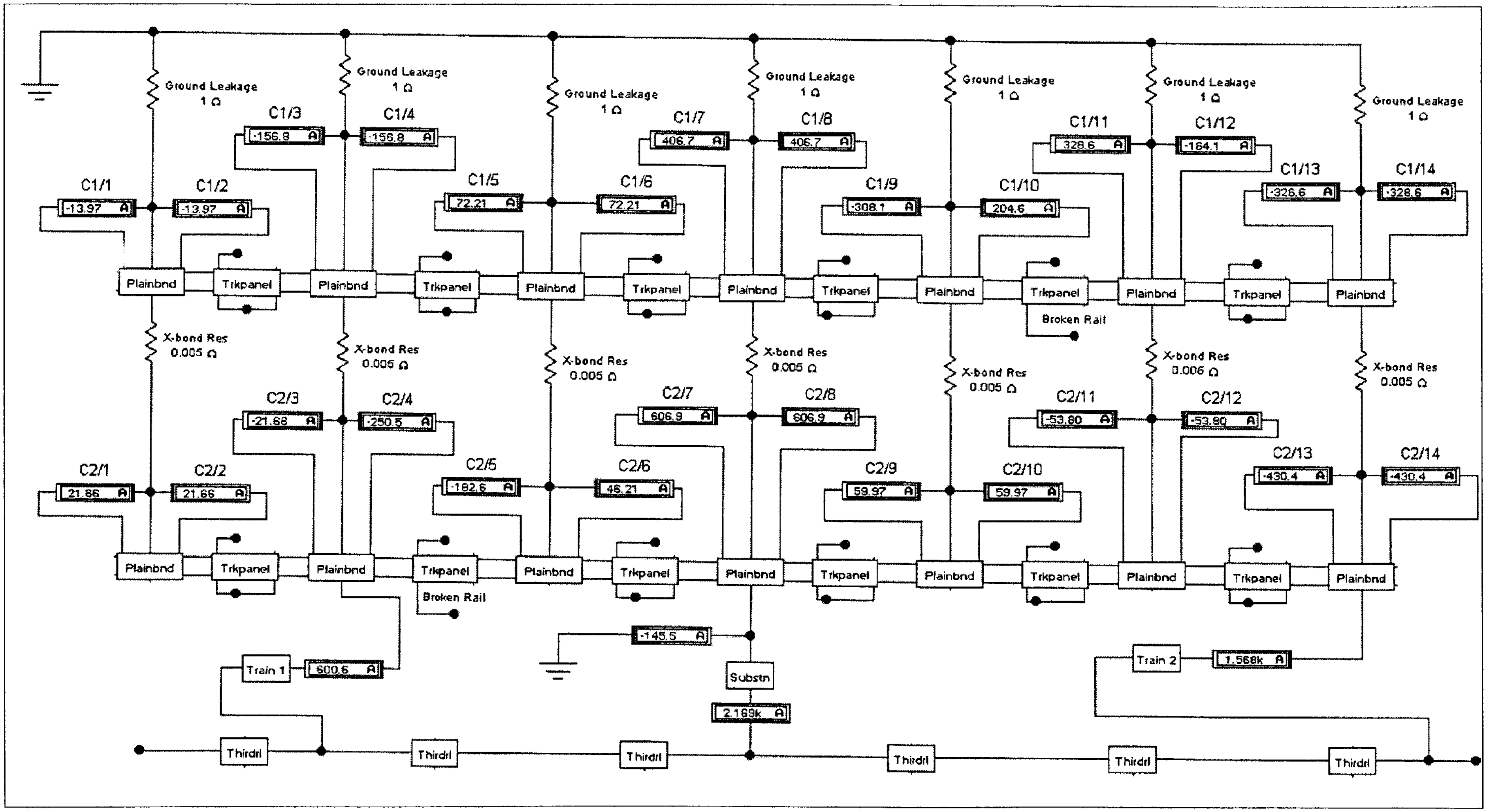

Figure A4. Current difference method, center substation, two trains, two rail breaks.

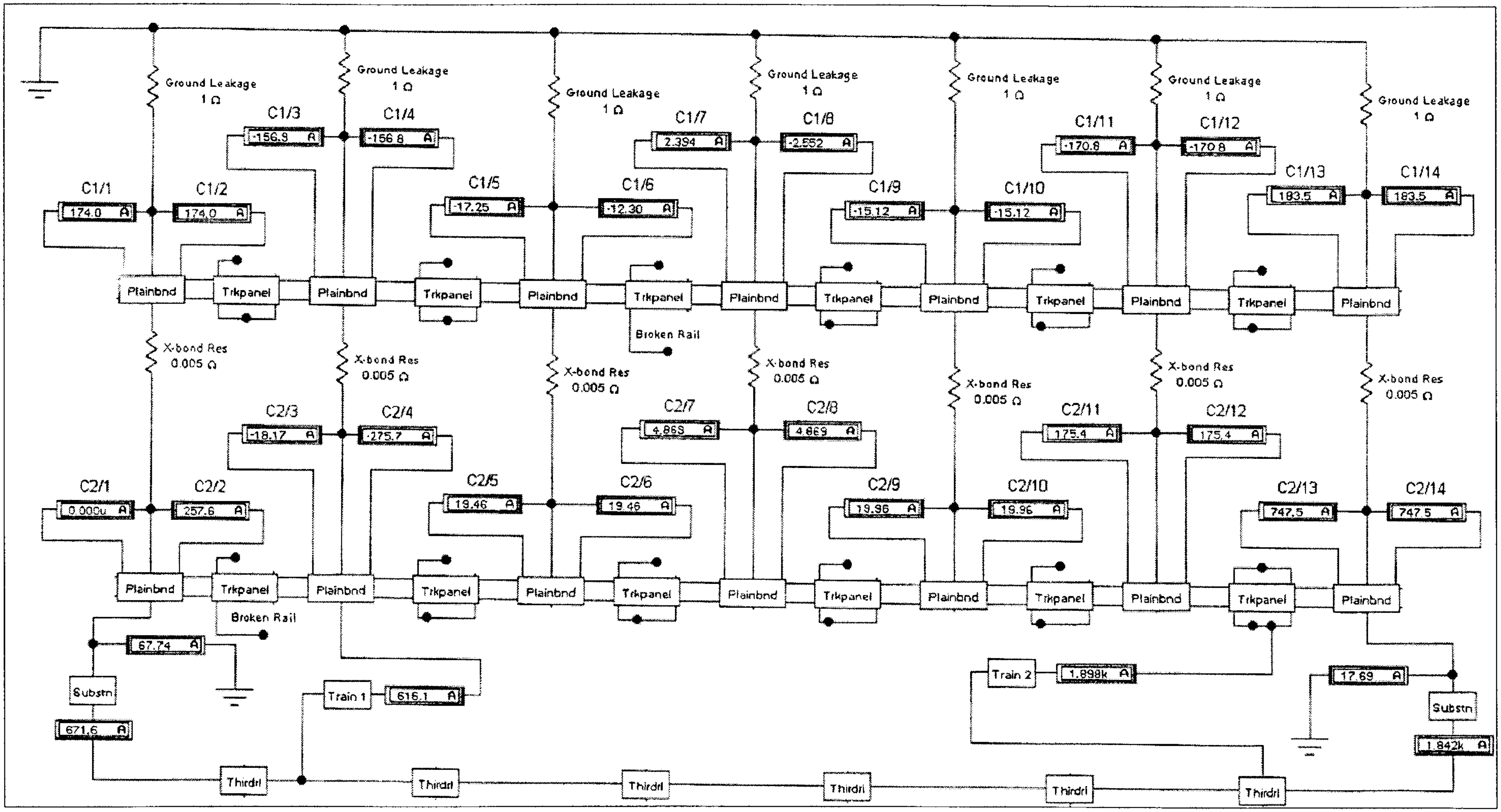

Figure A5. Current difference method, two interconnected substations, two trains, two rail breaks.

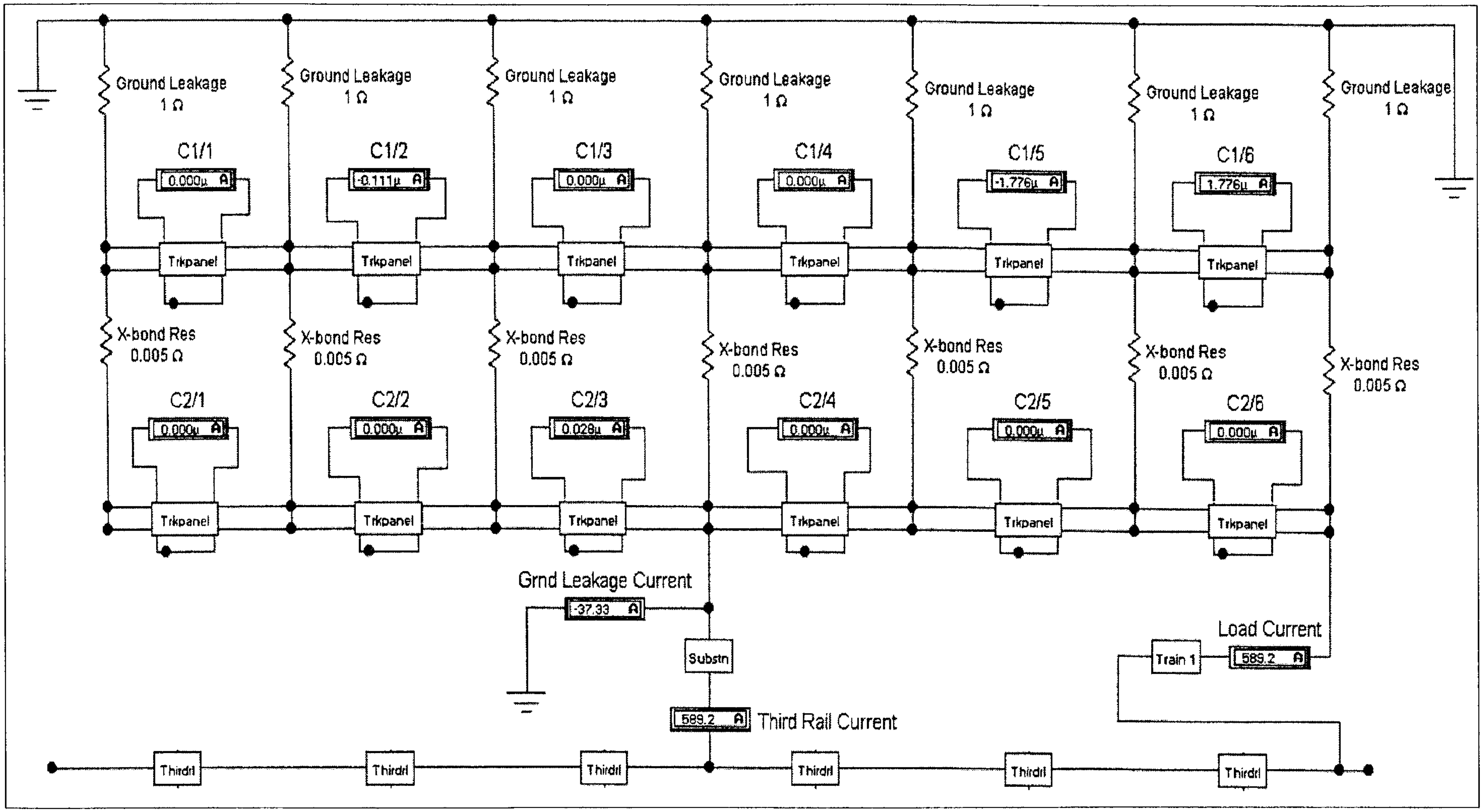

Figure A6. Center shunt method, center substation, one train, no rail break.

and "right" rail terminals of the Plainbnd subcircuits to represent the cross-bond current difference measurements. The ammeters have been labeled (e.g., C1/4) for use in data documentation. Values indicated on these ammeters represent the current steady-state solution of the network calculation.

In this example, the "train" loads have been connected into the lower cross-bond terminals on two of the Plainbnd subcircuits. Other alternative connection points were used during the course of this study, as will be demonstrated later. Based on information contained in the Electrical Engineers Handbook, "ground leakage" was incorporated into the model, as was a small level of resistance for the cross-bonding material (*2,* Ch. 23, Sec. 91, paragraph 216).

Figures A2 and A4 show the same basic case with one and then two "broken rails" introduced. The method used to introduce a broken rail is to remove the lower jumper on the relevant Trkpanel subcircuit. In these examples, each of the removed jumpers has been labeled as a "Broken Rail."

Figure A3 is the basic network used to represent the current difference method with two, interconnected substations. This network represents a two-track segment, 12,000 ft in length, with a substation at each end. The third rail is continuous throughout the track segment. Therefore, any load on the system can draw its power from both substations. In this example, the second method of connecting the "train" has been used. Subcircuit "Train 2" is connected into the lower jumper of the adjacent Trkpanel subcircuit. The jumper on the top of the same Trkpanel subcircuit has been linked to the second terminal on the top to simulate the rail-to-rail connection provided by the train axles. Figure A5 represents the same basic configuration with a "broken rail" added.

A3.4.2 Center Shunt Method

Figure A6 is a schematic of the center shunt method. The baseline example presented in Figure A6 represents a single train on a 1,200-ft long, two-track, segment. The electrical power is provided from a single substation, located at the center. Again, ground leakage and cross-bond resistance have been incorporated in the model. Since the cross-bonding plays a passive role (no measurement requirements) in this proposed method, the Plainbnd subcircuit has not been used. The lower jumper on the Trkpanel subcircuit has been completed to the second terminal to represent a continuous rail. An ammeter has been included in the completion of the top jumper to represent the rail-to-rail center shunt current measurement.

Similar to the current difference method examples, a sequence of network diagrams, representing other conditions applied to the current shunt method, is shown in Figures A7 through A9. Figure A7 depicts the baseline center shunt method with a broken rail. Figures A8 and A9 are the network diagrams for the two interconnected substation configurations, without and with a broken rail, respectively.

A3.4.3 Passive Resistor Loading

Figures A9 through A13, demonstrate the concept of a small load resistor bank to energize the traction current return circuits in the absence of a train.

A4 MODEL RESULTS

The results of modeling each method are discussed in the following sections.

A4.1 Current Difference Method

A4.1.1 General Functionality

The general functionality of the current difference method is demonstrated by the sequence of network diagrams, Figures A1 through A5. As described in Section A3.1, the traction return current is distributed among the running rails by the first available cross-bonds on either side of the load. The current is then collected from the rails by the substation negative feeder cables. The current is distributed among the available running rails in proportion to the resistance in the current path. Under normal conditions, the flow of current into and out of the two rails in a track is balanced substantially, as indicated by the current registered on the network diagram displays in Figure A1.

Introduction of a broken rail condition (Figure A2) significantly changes the current distribution in the network. First, the current levels in the rail-to-cross-bond connection on either side of the broken rail are increased greatly. Second, the current balance is destroyed, generating a large differential between the two rail-to-cross-bond connections. However, the current flow differential is confined to the track and the cross-bond locations on either side of the broken rail. While the actual current levels at the other locations may be significantly changed, the currents entering or leaving the rails at the non-broken rail locations are substantially balanced. Thus the basic mode of operation of the current difference rail break detection system, the first alternative system proposed by MTA-New York City Transit, has been demonstrated.

Introduction of a second broken rail (Figure A4) in the same electrical section causes a further change in traction current distribution, with the generation of large current differentials on either side of the second broken rail. The ability of the system to continue to detect the first broken rail is not impaired. Protection is also provided whether the train is on the track with the broken rail or not. Traction return currents generated on adjacent tracks are equally as effective in indicating the location of a broken rail as traction return currents generated in the track with the broken rail.

Finally, the system has the potential to operate under more than one traction power feed arrangement. Application of the

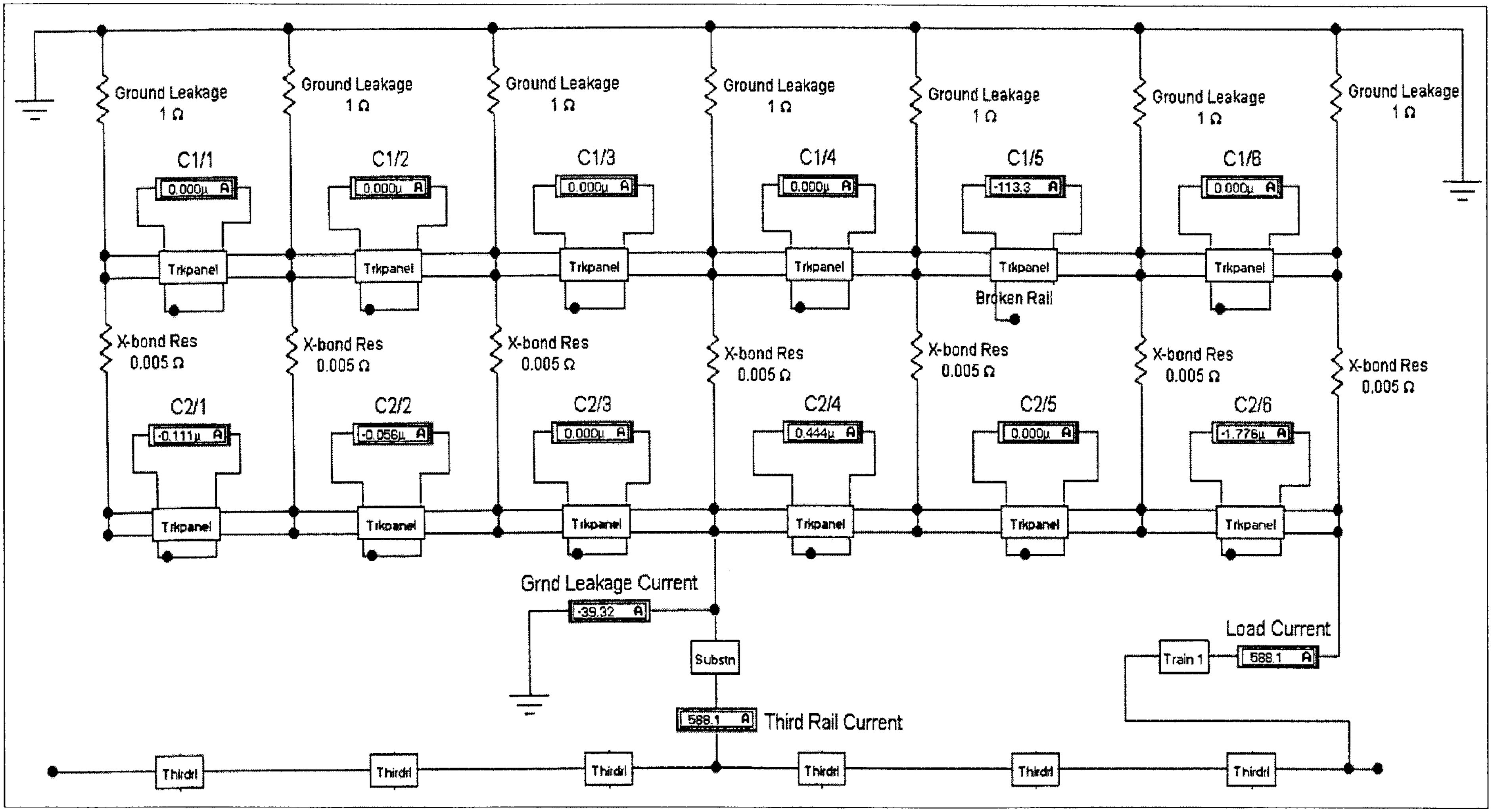

Figure A7. Center shunt method, center substation, one train, one rail break.

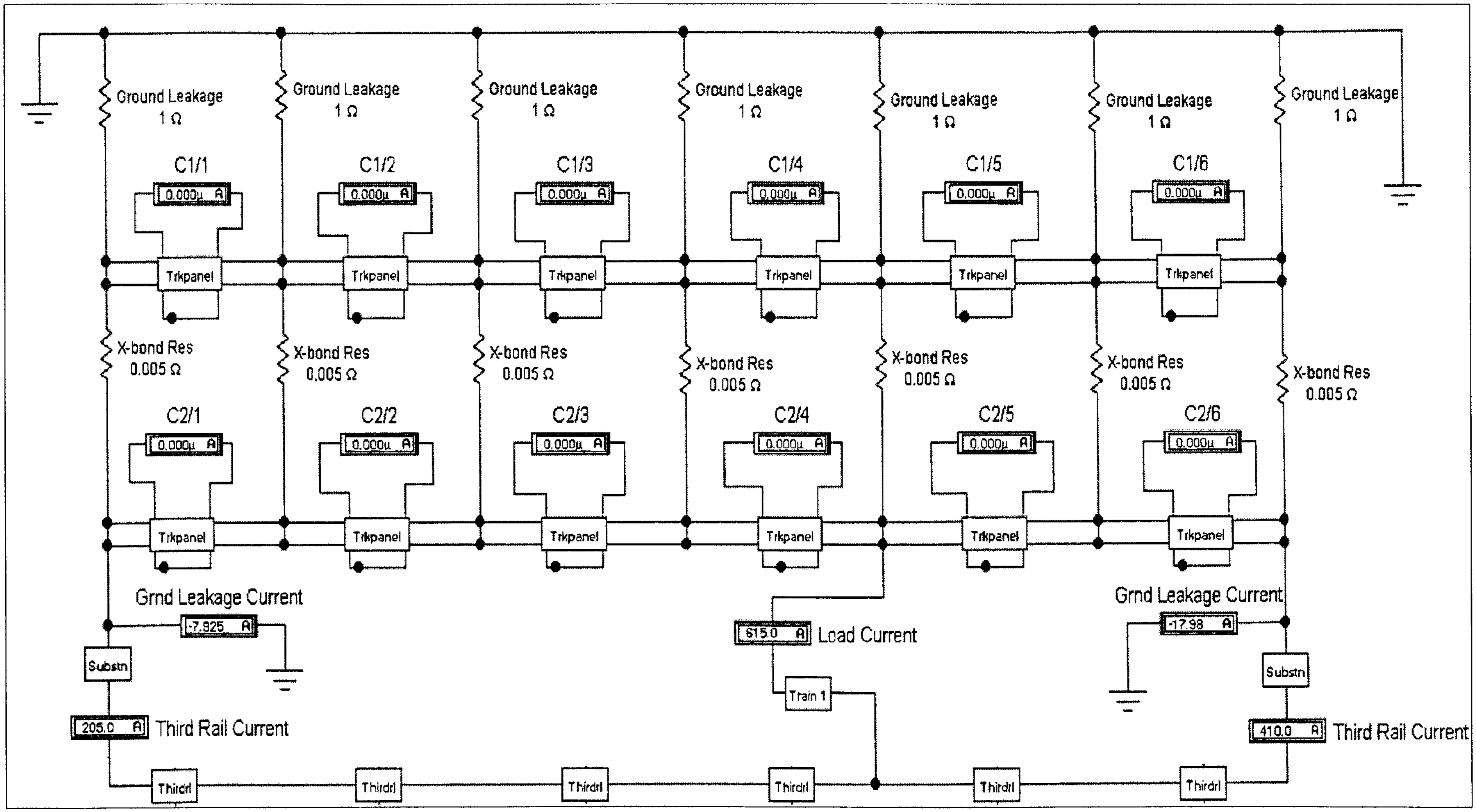

Figure A8. Center shunt method, two interconnected substations, one train, no rail break.

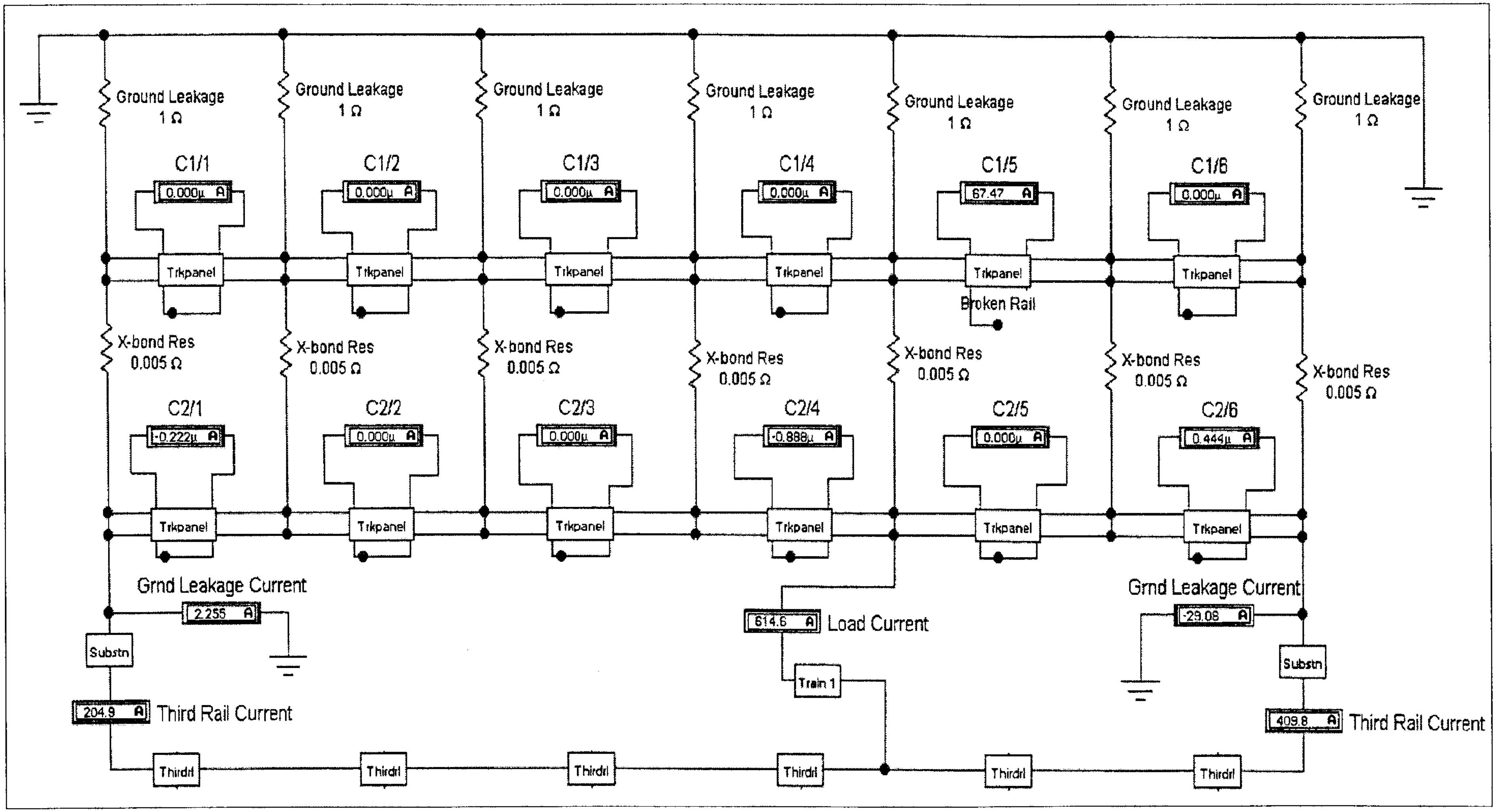

Figure A9. Center shunt method, two interconnected substations, one train, one rail break.

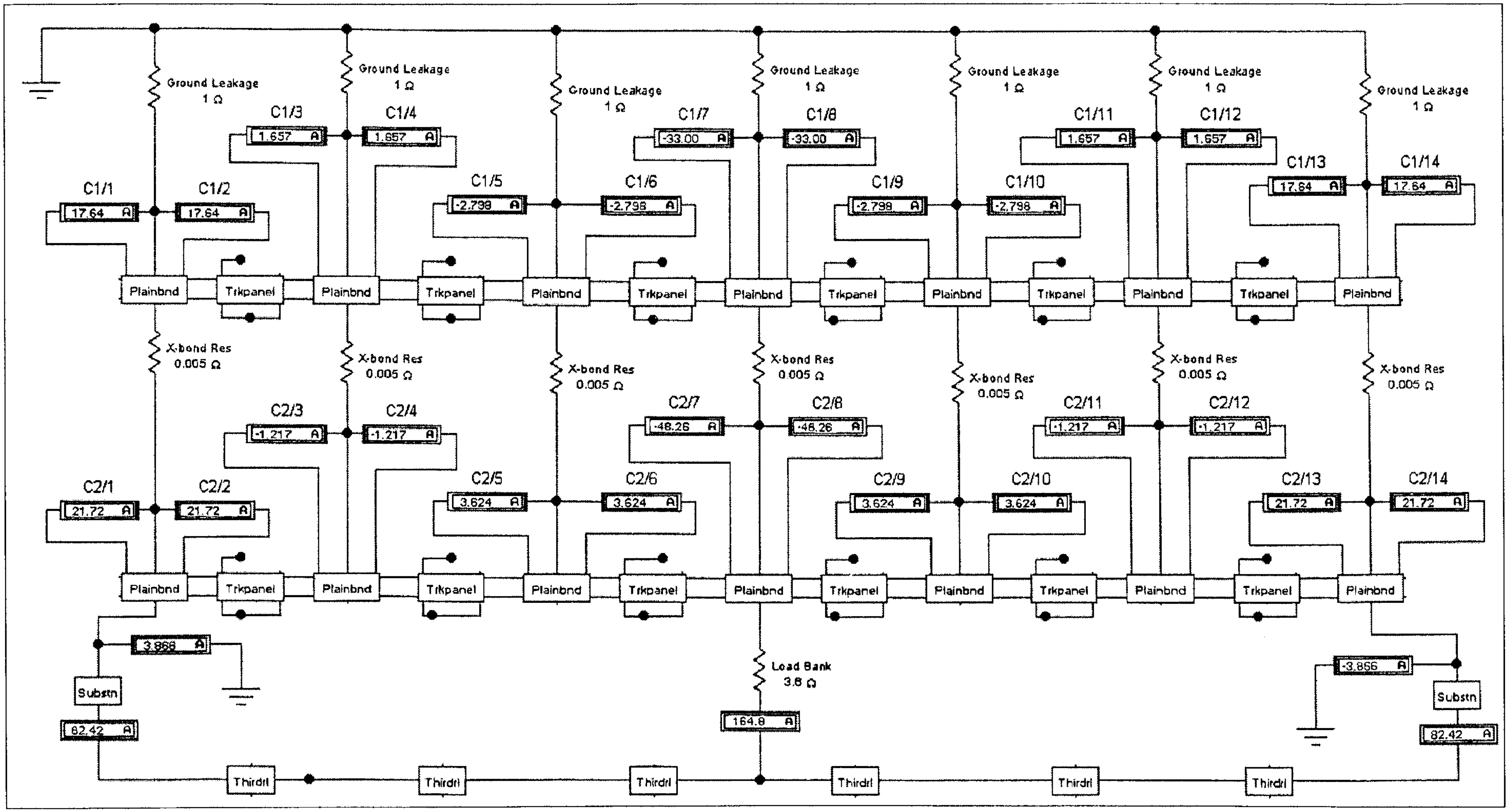

Figure A10. Current difference method, two interconnected substations, center load bank, no rail break.

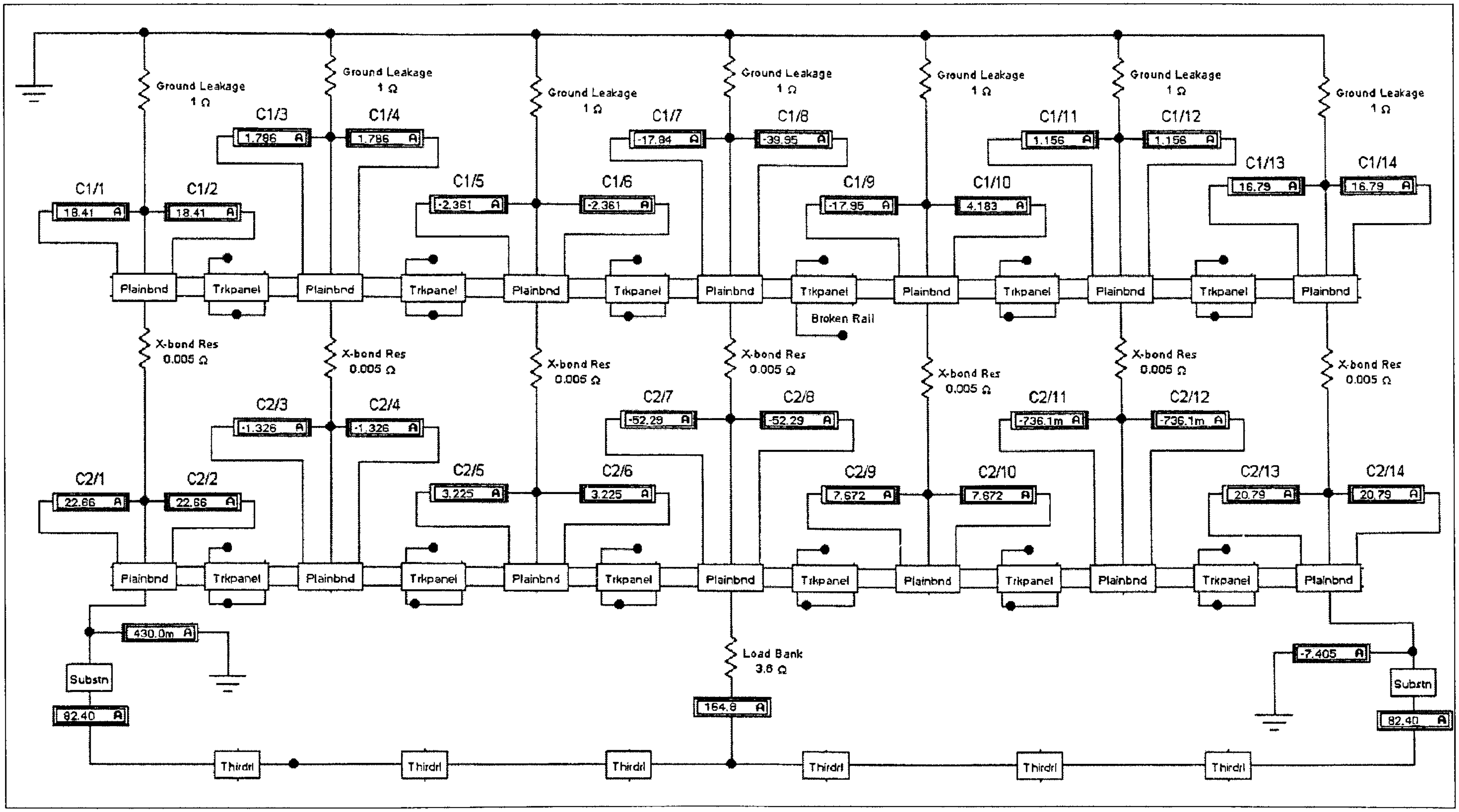

Figure A11. Current difference method, two interconnected substations, center load bank, one rail break.

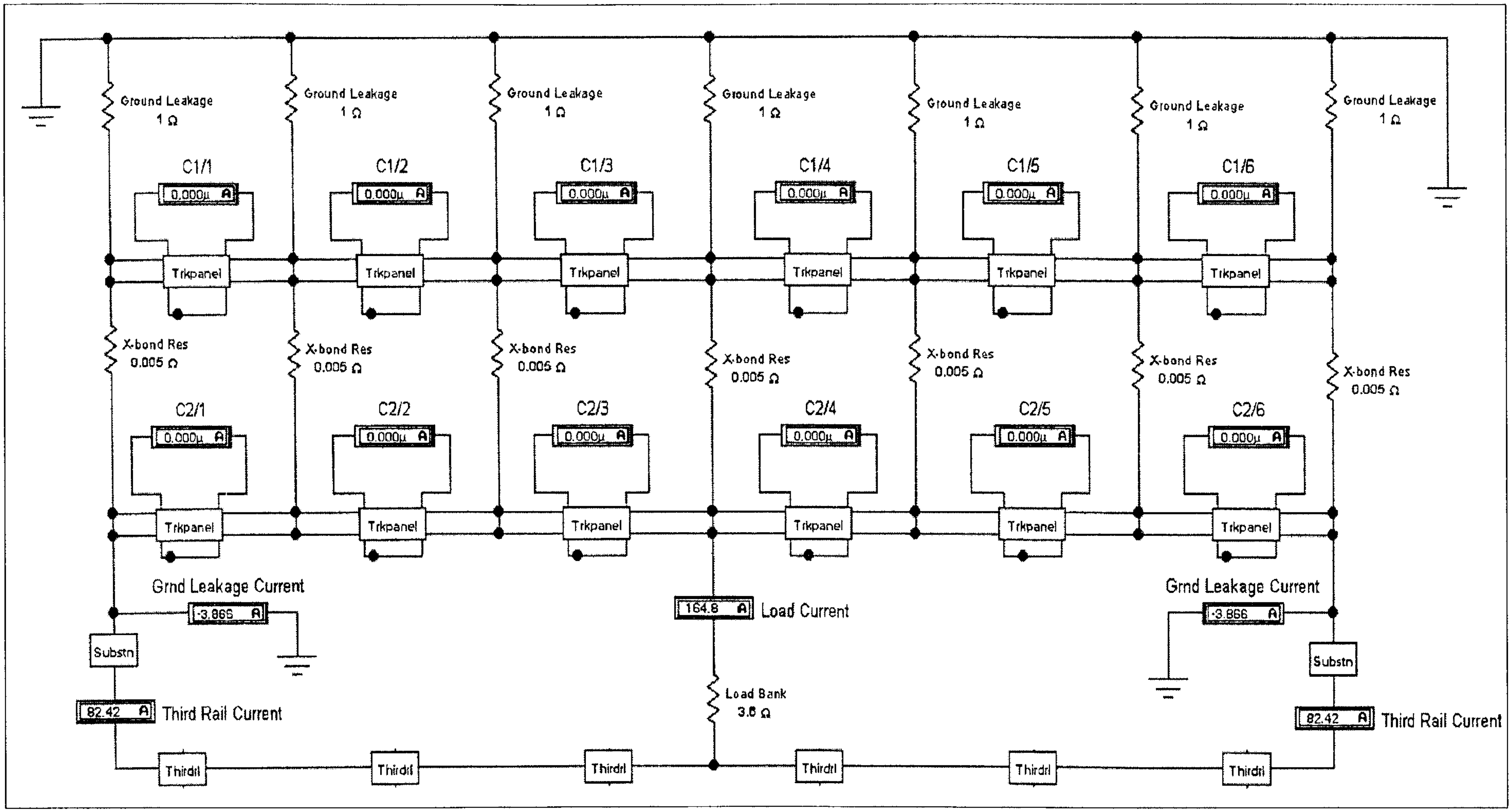

Figure A12. Center shunt method, two interconnected substations, center load bank, no rail break.

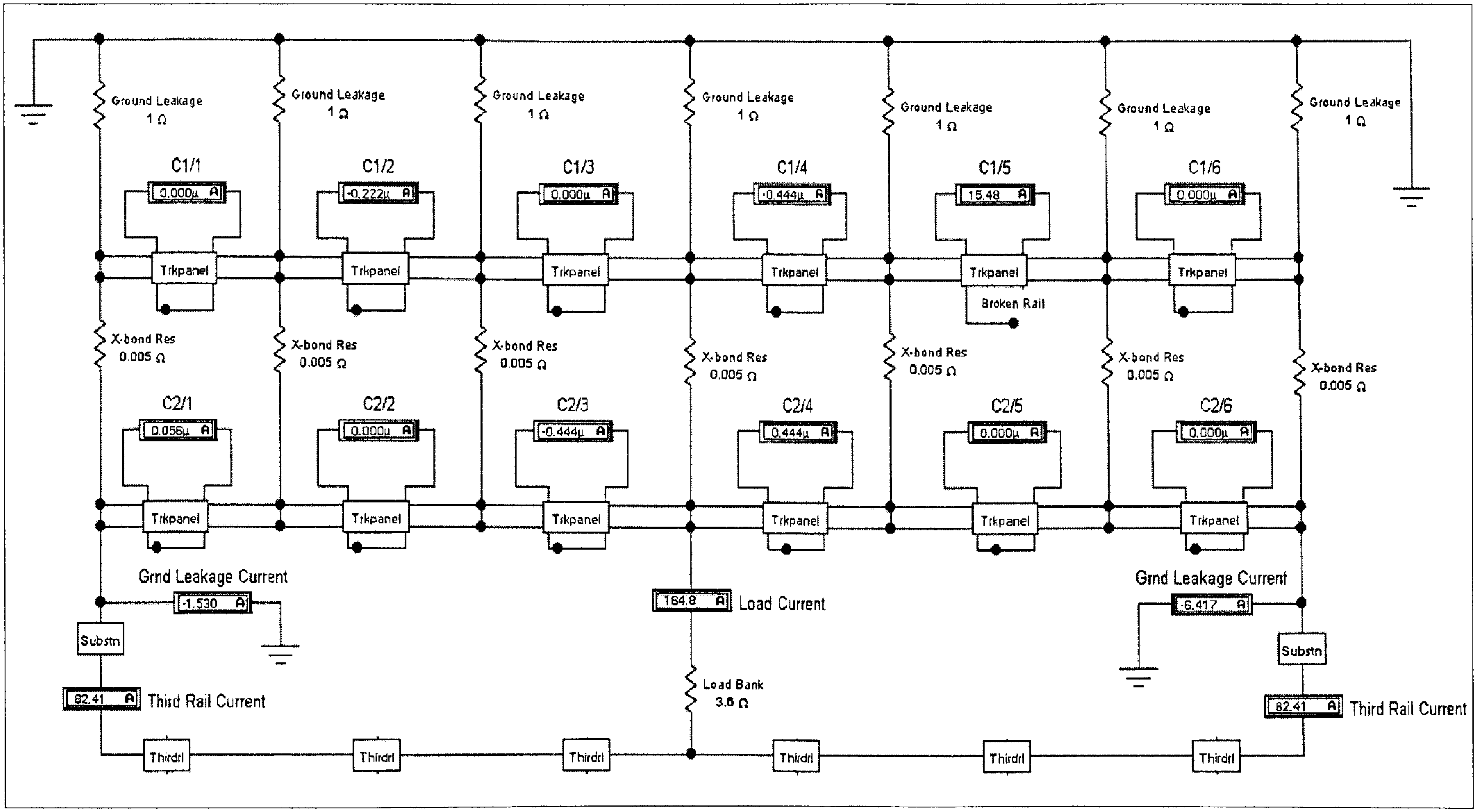

Figure A13. Center shunt method, two interconnected substations, center load bank, one rail break.

system to an interconnected substation arrangement (Figures A4 and A5) demonstrates the same basic functionality as the center feed arrangement.

A4.1.2 Effect of Train Location and Traction Power Level

A series of simulations was performed to determine the effect of train location on the ability of the system to detect a broken rail condition. This was accomplished by moving the point of connection of the "train" incrementally along the track segment and documenting the network analysis current balance data at each data point. By virtue of the available connection points, this procedure provided data at 1,000-ft intervals. Using the center substation configuration, data sets were produced for a full traction power case with no broken rail. Data are recorded in Table A1. Data sets were then produced for a broken rail condition at three traction power levels, which were full power, quarter power, and coasting power. These data sets are listed in Tables A2, A3 and A4. The quarter power with broken rail condition was repeated for the two interconnected substations case, the data set for which is presented in Table A5.

Based on the simulation data, the current difference levels expected from a rail break in a two-track section are on the order of 30 percent of the total traction power. For three or more tracks the expected current difference, as a proportion of the total traction power, will be reduced approximately by the inverse of the number of parallel tracks. For a typical transit trainset, minimum current difference levels on the order of 50 Amp could be expected from a coasting train operating in the vicinity of a broken rail. This compares with a maximum current difference value of 500 Amp for an accelerating train and 200 Amp for an average (speed maintaining) power draw. The feasibility of detecting the minimum predicted difference, as the result of a broken rail, rather than from other system irregularities, is the key to determining the potential reliability of a broken rail detection system based on this technology.

Another key to the potential application of a current difference detector is the available operating window. Figure A7 is a plot of the train location versus the simulated current difference, based on the average traction current draw. The double "mirror imaged" lines for each case result from plotting the characteristic for the cross bond on either side of the broken rail. In the example selected for this study, the broken rail is located between 8,000 ft and 9,000 ft. Two power configurations are presented in the graph: the center substation and the two interconnected substations. In the center substation case, there is no detectable current difference until the train moves beyond the broken rail. This is a logical finding, since the generation of a current difference can only be expected when the broken rail is between the load and the source of power. This means that for a center substation feed arrangement, the window for the detection of a rail break at the extreme ends of the traction power section is limited to train occupancy of one 2,000-ft track section.

The two substation feed arrangement provides a much better window of opportunity for detection. This results from the natural tendency of the load to be shared between the two power sources and current to be flowing across the broken rail section all the time that the train is between the substations. A minor disadvantage is that the peak value of the current difference is less than the center substation case. Unfortunately, the electrical feed arrangement is not a selectable option, having been determined by other system design considerations. Thus, the current difference broken rail detector system must be prepared to operate reliably in the worst-case scenario.

A4.2 Center Shunt Current Method

A4.2.1 General Functionality

The basic traction current return circuit functionality is not affected by the installation of the mid-point rail-to-rail current shunt. The cross bonding still distributes the traction return current among the running rails. Even when the train is near a

TABLE A1 Cross-bond differential current design—center substation, one train, full traction current, no rail break

Location (Ft)	Center Substn	Substn Ground	C1/1 & C1/2	C1/3 & C1/4	C1/5 & C1/6	C1/7 & C1/8	C1/9	C1/10	C1/11	C1/12	C1/13 & C1/14	Left X-bond Differential Value	Left X-bond Differential Ratio	Right X-bond Differential Value	Right X-bond Differential Ratio
	Current (Amps)														
0	1588	-191	-334	-18	33	286	29	29	4	4	1	0	0%	0	0%
1000	1633	-182	-183	-167	19	295	30	30	4	4	1	0	0%	0	0%
2000	1701	-175	-22	-328	5	309	32	32	4	4	1	0	0%	0	0%
3000	1753	-148	-9	-181	-155	309	32	32	4	4	1	0	0%	0	0%
4000	1831	-121	5	-25	-329	312	32	32	4	4	1	0	0%	0	0%
5000	1897	-63	3	-13	-171	161	16	16	2	2	1	0	0%	0	0%
6000	2000	0	0	0	0	0	0	0	0	0	0	0	0%	0	0%
7000	1897	-63	1	2	17	162	-170	-170	-13	-13	3	0	0%	0	0%
8000	1831	-121	1	4	32	312	-329	-329	-25	-25	5	0	0%	0	0%
9000	1753	-148	1	4	32	309	-155	-155	-181	-181	9	0	0%	0	0%
10000	1701	-175	1	4	32	309	5	5	-328	-328	-22	0	0%	0	0%
11000	1633	-182	1	4	30	295	19	19	-167	-167	-183	0	0%	0	0%
12000	1588	-191	1	4	29	286	33	33	-18	-18	-334	0	0%	0	0%

TABLE A2 Cross-bond differential current design—center substation, one train, full traction current, one rail break

	Current (Amps)											Left X-bond Differential		Right X-bond Differential	
Location (Ft)	Center Substn	Substn Ground	C1/1 & C1/2	C1/3 & C1/4	C1/5 & C1/6	C1/7 & C1/8	C1/9	C1/10	C1/11	C1/12	C1/13 & C1/14	Value	Ratio	Value	Ratio
0	1588	-191	-334	-18	33	286	34	27	-1	5	1	7	0%	-6	-0%
1000	1633	-182	-183	-167	19	295	35	28	-1	6	1	7	0%	-7	-0%
2000	1701	-175	-22	-328	5	309	36	30	-1	6	1	6	0%	-7	-0%
3000	1753	-148	-9	-181	-155	309	36	30	-1	6	1	6	0%	-7	-0%
4000	1831	-121	5	-25	-329	313	37	30	-1	6	1	7	0%	-7	-0%
5000	1897	-62	3	-13	-171	162	19	16	-1	3	1	3	0%	-4	-0%
6000	2000	0	0	0	0	0	0	0	0	0	0	0	0%	0	0%
7000	1897	-63	1	2	17	161	-181	-166	-3	-18	3	-15	-1%	15	1%
8000	1831	-122	1	4	32	312	-349	-320	-6	-34	6	-29	-2%	28	2%
9000	1749	-157	1	4	31	301	-337	-71	2	-264	-2	-266	-15%	266	15%
10000	1690	-190	1	4	30	294	-329	159	10	-478	-10	-488	-29%	488	29%
11000	1600	-198	1	4	29	281	-314	173	169	-317	-169	-487	-30%	486	30%
12000	1576	-207	1	4	28	271	-303	187	320	-171	-320	-490	-31%	491	31%

center shunt, there is no significant rail-to-rail current flow at that location (unless there are inconsistent wheel-to-rail electrical contact conditions). Thus, in both the center substation (Figure A6) and the interconnected substation (Figure A8) baseline cases, there are no center shunt currents indicated at any of the locations. When the broken rail is introduced, both substation configurations result in a current flow in the center shunt adjacent to the broken rail (Figures A7 and A9). Thus the basic mode of operation of the center shunt rail break detection system, the second alternative system proposed by MTA-New York City Transit, has been demonstrated.

A4.2.2 Effect of Train Location

The first observation is that the center shunt current levels are predicted to be approximately 60 percent of the predicted current differences in the cross-bond connection for the same conditions. Thus, a minimum current resolution of approximately 30 Amp would be required for the center shunt method to be a feasible undertaking.

The relationship of the center shunt current with train location is plotted in Figure A8 for both substation feed options. The form of both characteristics is the same as for the current difference method. The detection window is limited to where the train has progressed beyond the broken rail, relative to the center substation. Alternatively, the interconnected substations provide a wider detection window, but at a reduced detection level.

A4.3 Effect of "Real World" Conditions

A4.3.1 Grounding Faults

An attempt was made to use the model to investigate the potential for rail-to-ground faults to cause malfunctions of either of the two candidate detection methods. Two possible malfunction scenarios were addressed. The first scenario addressed was to determine the level of ground fault (defined as the resistance between the fault point and earth ground) that would be necessary to generate a measurement offset

TABLE A3 Cross-bond differential current design—center substation, one train, quarter traction current, one rail break

	Current (Amps)											Left X-bond Differential		Right X-bond Differential	
Location (Ft)	Center Substn	Substn Ground	C1/1 & C1/2	C1/3 & C1/4	C1/5 & C1/6	C1/7 & C1/8	C1/9	C1/10	C1/11	C1/12	C1/13 & C1/14	Value	Ratio	Value	Ratio
0	590	-71	-124	-7	12	106	13	10	0	2	0	3	1%	-2	-0%
1000	596	-66	-67	-61	7	108	13	10	0	2	0	3	1%	-2	-0%
2000	605	-62	-8	-117	2	110	13	11	0	2	0	2	0%	-2	-0%
3000	611	-51	-3	-63	-54	108	13	10	0	2	0	3	0%	-2	-0%
4000	621	-41	2	-8	-112	106	12	10	0	2	0	2	0%	-2	-0%
5000	628	-21	3	-4	-56	54	6	5	0	1	0	1	0%	-1	-0%
6000	638	0	0	0	0	0	0	0	0	0	0	0	0%	0	0%
7000	628	-21	0	1	6	53	-60	-55	-1	6	1	-5	-1%	-7	-1%
8000	621	-41	0	1	11	106	-118	-109	-2	-12	2	-9	-1%	10	2%
9000	611	-55	0	1	11	105	-118	-25	1	-92	-1	-93	-15%	93	15%
10000	604	-68	0	1	11	105	-118	57	4	-170	-4	-175	-29%	174	29%
11000	595	-72	0	1	11	103	-115	63	62	-116	-62	-178	-30%	178	30%
12000	588	-77	0	1	10	101	-113	70	119	-64	-119	-183	-31%	183	31%

TABLE A4 Cross-bond differential current design—center substation, one train, no traction current (auxiliaries only), one rail break

Location (Ft)	Current (Amps) Center Substn	Substn Ground	C1/1 & C1/2	C1/3 & C1/4	C1/5 & C1/6	C1/7 & C1/8	C1/9	C1/10	C1/11	C1/12	C1/13 & C1/14	Left X-bond Differential Value	Left X-bond Differential Ratio	Right X-bond Differential Value	Right X-bond Differential Ratio
0	211	-25	-44	-2	4	38	4	4	0	1	0	0	0%	-1	-0%
1000	212	-24	-24	-22	2	38	5	4	0	1	0	1	0%	-1	-0%
2000	213	-22	-3	-41	1	39	5	4	0	1	0	1	0%	-1	-0%
3000	214	-18	-1	-22	-19	38	4	3	0	1	0	1	0%	-1	-0%
4000	215	-14	1	-3	-39	37	4	4	0	0	0	0	0%	0	0%
5000	216	-7	0	-1	-19	18	2	2	0	0	0	0	0%	0	0%
6000	217	0	0	0	0	0	0	0	0	0	0	0	0%	0	0%
7000	216	-7	0	0	2	18	-21	-19	-1	-2	0	-2	-1%	1	0%
8000	215	-14	0	0	4	37	-41	-38	0	-4	-1	-3	-1%	4	2%
9000	214	-19	0	0	4	37	-41	-9	0	-32	0	-32	-15%	32	15%
10000	213	-24	0	0	4	37	-42	20	1	-60	1	-62	-29%	61	29%
11000	212	-26	0	0	4	37	-41	23	22	-41	22	-64	-30%	63	30%
12000	211	-28	0	0	4	36	-41	25	43	-23	43	-66	-31%	66	31%

equivalent to 50 percent of the minimum detection level and trigger a false alarm. The second scenario was to determine the ground fault level that would be necessary at the broken rail ends to effectively bridge the electrical circuit and cause a failure of the system to detect the broken rail. Again, the fault level threshold was defined as the resistance to earth ground necessary to reduce the fault current to less than 50 percent of the minimum detection level.

This investigation exposed the limits of the simple model approach. It was observed that applying simulated ground faults through a leakage resistor could cause both measurement systems to respond in a similar manner. It was found that if the leakage resistor exceeded 0.5 ohms, then the measurement error was not significant. If the leakage resistor was less than 0.2 ohms then the detection capability was compromised. Therefore, the significance of rail-to-ground faults on the system integrity will be site-specific. For example, at the TTC facility in Pueblo, Colorado, it is difficult to generate ground faults with an effective resistance to earth ground of less than 0.6 ohms. In the eastern United States, where the ground moisture and track surface conditions are wetter, it may be possible to generate ground faults with lower effective resistance.

A4.3.2 Rail Surface Contamination

One of the assumptions made in the modeling study was that the traction current return from the train wheelsets to the running rails was balanced. The presence of rail surface contamination would affect the initial current balance in the two running rails. However, this imbalance would be equalized at the first rail-to-rail bond location. Any instrumentation (current difference or center shunt current) in that bond may see this as a transient noise effect. The signal processing procedures would need to eliminate spurious data.

TABLE A5 Cross-bond differential current design—two interconnected substations, one train, quarter traction current, one rail break

Location (Ft)	Current (Amps) First Substn	First Substn Ground	Second Substn	Second Substn Ground	Train Load	C1/1& C1/2	C1/3& C1/4	C1/5& C1/6	C1/7& C1/8	C1/9	C1/10	C1/11	C1/12	C1/13& C1/14	Left X-bond Differential Value	Left X-bond Differential Ratio	Right X-bond Differential Value	Right X-bond Differential Ratio
0	638	0	0	0	638	0	0	0	0	0	0	0	0	0	0	0%	0	0%
1000	576	-1	52	-6	629	49	-57	-5	1	12	-5	-10	7	10	17	3%	-17	-3%
2000	519	-22	104	-12	623	98	-113	-9	1	24	-9	-20	13	20	33	5%	-33	-5%
3000	463	-22	154	-21	617	91	-57	-65	-4	34	-14	-29	19	29	48	8%	-48	-8%
4000	410	-22	205	-29	615	86	-2	-120	-8	44	-19	-38	25	38	63	10%	-63	-10%
5000	357	-18	255	-36	612	76	3	-64	-63	49	-28	-47	30	47	77	13%	-77	-13%
6000	306	-14	306	-43	612	65	7	-9	-119	55	-38	-57	35	57	93	15%	-92	-15%
7000	255	-8	357	-47	612	55	6	-4	-63	5	-96	-67	34	67	101	17%	-101	-17%
8000	205	-3	410	-50	615	46	6	2	-7	-45	-155	-77	32	77	110	18%	-109	-18%
9000	154	-6	463	-37	617	33	4	1	-4	-35	-79	-87	-44	87	44	7%	-43	-7%
10000	104	-10	519	-23	623	21	3	1	0	-25	-3	-98	-121	98	-22	-4%	23	4%
11000	121	-24	500	0	621	22	2	1	0	-24	5	-37	-66	37	-29	-5%	29	5%
12000	0	0	638	0	638	0	0	0	0	0	0	0	0	0	0	0%	0	0%

A4.3.3 Special Track Work

The modeling study was limited to the simulation of a system with four parallel rails. The additional electrical paths caused by special track work, such as switches and crossings, and guard rails, will affect the characteristics of the traction current return. In most transit applications, there is a high proportion of special track work in the system and any broken rail detection system would be required to function reliably in that environment. In some cases, guard rails in electrical contact with the running rails may even shunt the traction current past a broken running rail. However, this problem may not be any different from a conventional track circuit rail break system.

A4.4 Data Processing Techniques

One of the major developments required to turn the proposed detection methodology into a reliable broken rail protection system is timely data processing capability. Modern computer technology has greatly enhanced the potential local processing power. With this, the use of enhanced analysis and diagnostic tools, such as neural network analysis, can be readily applied on a site-by-site basis. As an example, the acoustic bearing detector system, currently under development by TTCI, uses such techniques to process the trackside data and flag bad actors. The objective, stated in the MTA-New York City Transit reference paper, for a simple system is highly desirable. However, on the basis of the sample data provided in the same reference paper and the results of this study, the need for a more sophisticated data processing technique is indicated.

A4.5 Alternative Electrical Loading of the Traction Current Return Circuits

One of the observations resulting from the modeling analysis was the need for a train to be in the vicinity of the broken rail for either of the systems to detect it. Furthermore, if the broken rail is near the end of the substation electrical distribution section, the time available to detect the fault can be relatively short. One of the possible options evaluated as part of the modeling study was to determine whether a small dummy load at trackside could be used to test for a broken rail. In the basic concept, the test resistor could be applied to the third rail before an approaching train entered the section. The time that the resistor would be required on line would be on the order of a few seconds, depending on the time constant of the measuring system. Such a system would eliminate any spurious wheel/rail effects and would simplify the application of neural network analysis techniques.

The modeling analysis indicated that a load resistor, dissipating approximately 100 kW, could generate a detectable signal in either of the two candidate measuring systems. Figures A9 and A10 present the predicted response of the current difference and center shunt systems, respectively, to a broken rail at various locations throughout the analyzed track segment. These diagrams clearly show the sequencing of the broken rail indication with the location of the actual break. These simulations were conducted for the two interconnected substations, with the load resistor applied at the center (see Figures A10 to A13). In principle, this concept would be equally as effective in the single substation configuration but the load resistor switching requirements may be slightly more complex.

A5 CONCLUSIONS

Based on the results of the review of the MTA-New York City Transit reference documentation and analysis of the modeling results, the following conclusions have been made:

- Both the cross-bond differential current and the center shunt current measuring systems have the potential to detect traction return current imbalance because of a broken rail.
- Both systems will provide the same level of protection from traffic on adjacent tracks.
- Based on current knowledge, neither system has a clear-cut advantage over the other. While the current difference method is applied to the existing bonding arrangement, the instrumentation requirements are more complex than the center shunt current method.
- Both systems can only detect a broken rail when it is located between the point of loading (the train) and the source of the traction power (substation). This may significantly reduce the detection window for broken rails near the end of an electrical section.
- Based on limited simulation data, the current drawn from a coasting train should exceed the minimum measurement threshold of either system.
- From a technical perspective, a strategically placed switchable load resistor could improve the advance protection of an approaching train.
- The effects of special track work and local conditions, such as wet or icy track and ground faults, require further clarification.
- Advanced data analysis techniques, such as neural network analysis, may be necessary to augment the raw measurements to provide a reliable product.
- Both systems have sufficient promise to merit further investigation.

A6 RECOMMENDATIONS

The following recommendations are offered as a result of the current study:

- Further work should be performed to clarify some of the outstanding issues identified in this evaluation. For example, this work should include a literature search as well as local measurement to determine ground fault characteristics prevalent at a typical transit property.
- Consideration should be given to implementing a small pilot installation on a typical transit site, involving, at a minimum, potential system designers and transit system personnel.

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