Analyzing Transit AC and DC Traction Power Networks

Richard N. Rauceo
LTK Engineering Services
Boston, MA

Tristan Kneschke, PE
LTK Engineering Services
Ambler, PA

Michael K. Fitzgerald
Massachusetts Bay Transportation Authority
Boston, MA

John A. Martin
Massachusetts Bay Transportation Authority
Boston, MA

ABSTRACT

Numerous software programs have been developed to analyze ac power utility systems and dc transit traction power networks. Often, the two systems are studied separately, as the impact of dc loads on the utility medium voltage system is not significant in many cases.

However, this is not always the case. Some US transit agencies have their own ac distribution system, using medium voltage to supply traction power substations and auxiliary loads. The ac distribution system is normally fed from several utility sources to mitigate the impact from a partial utility outage. This is the case with the Bay Area Rapid Transit District (BART) and Sound Transit's tunnel (ST) systems. In the unique case of the Massachusetts Bay Transportation Authority (MBTA) system, the agency's power to their 13.8 kV ac distribution system is distributed from a centralized location known as South Boston Power Complex (SBPC). Normally, the SBPC receives power from NSTAR's 115 kV grid, but if necessary, backup power can be provided from MBTA's own 68 MVA combustion turbine generator.

In the aforementioned ac distribution systems, the dc substation loads usually present the heaviest power demand. Due to the nature of transit system operation, the substation power demand varies rapidly which directly influences the ac load flow. Consequently, the interactions between the two systems can only be determined by using a comprehensive ac & dc study approach. This paper will present the methodology and tools being applied to MBTA's distinct distribution system in order to perform comprehensive ac and dc load-flow, short-circuit, and protective relay device coordination studies.

APPLICABILITY TO OTHER AGENCIES

While this study is being performed for the MBTA, the work is also applicable to other transit agencies. Agencies that have their own ac distribution systems may utilize the approach outlined herein as a guide to assess and study their particular system.

INTRODUCTION

DC Traction Power Substations (TPSS) are normally fed from power utility ac feeders. In some traction power systems, each TPSS is fed from one or more dedicated utility ac feeders so that, in the event of a loss of an ac feeder, disruption of system operation is minimized and transit service can be maintained at the scheduled headways. As with any power system, it is the responsibility of the power utility to provide protection up to the point of common coupling (PCC), and the transit agency's responsibility is downstream of the PCC as illustrated in Figure 1. In providing ac protection for the substations, the transit agency is responsible for ensuring that substation protection is coordinated with the power utility protection and approved by the utility.

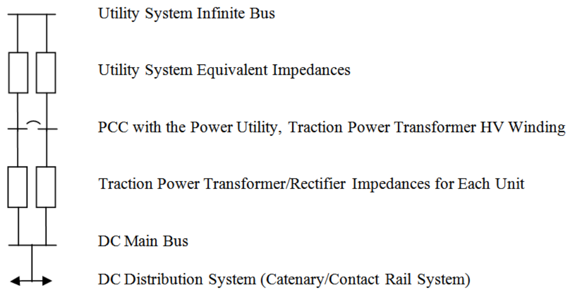


Figure 1: Graphical Representation of Power Utility System & Traction Power Substation Interface

Transit agencies such as BART, Sound Transit, and the MBTA own their ac distribution system; their immunity to partial utility ac outage is attributed to utility source configuration and associated feeder system arrangements that provide a high level of redundancy. As an additional level of redundancy, the MBTA owns a combustion turbine generator that can be operated in the event of a major power utility outage or blackout.

BACKGROUND

Over the last 15 years, the MBTA's 13.8 kV distribution system has been steadily expanding and the traction power load demand has increased significantly. In addition, new traction power substations have been added to the ac network, and several substation feeding arrangements were reconfigured. Furthermore, the short-circuit level at the NSTAR PCC with MBTA increased due to a reconfiguration of the NSTAR substation. As a result, a new comprehensive system study is required to understand system impact and ensure continued safe, reliable, and efficient operation of this vital system.

MBTA's SYSTEM CONFIGURATION & OPERATION

This section describes the various system elements of the ac network to provide a general understanding of the MBTA's distribution system which is referred to later in the paper during the discussion of the ac and dc analysis. Figure 2 and Figure 3 provide a schematic overview of the distribution system. In Figure 2, the ac network drawing is referred to as the "spider diagram" due multiple feeder paths and interconnections to TPSS.

Power Supply System

The network receives power from two sources:

- NSTAR's 115 kV transmission system via two MBTA 115 kV copper pipe-type transmission cables that supply four 115 kV/13.8 kV step-down transformers.
- MBTA's combustion turbine generator.

Under normal operating conditions, the two 115 kV cables and the four transformers are in service supplying the MBTA's 13.8 kV network. The generator is on cold standby and can be connected to the system when necessary.

South Boston Power Complex (SBPC)

Power Generating Unit

The MBTA combustion turbine generator is used during an NSTAR system outage and high power demand periods when the Independent System Operator-New England (ISO-NE) requests additional capacity support from the MBTA. In this case, the MBTA can either provide power directly into the NSTAR system or assist NSTAR by reducing its load requirements. During these requests, all operation and maintenance costs are covered by ISO-NE. In addition, NSTAR and ISO-NE compensate the Authority for power reserve, black start, and quick start capability.

ISO-NE is an organization that oversees the operation of New England's bulk electric power system and transmission lines generated and transmitted by its member utilities. MBTA also purchases power on the wholesale market.

115 kV/13.8 kV Transformers

The power from the NSTAR system to the MBTA's 13.8 kV distribution system is supplied by four (4) National Industries' outdoor 115 kV (delta)/13.8 kV (wye) step-down 24/32/40 MVA OA/FA/FA rated transformers. Normally all four (4) transformers are in service. The neutral points of all four transformers secondary windings are connected to a common grounding resistor.

Series Reactors

The combustion turbine generator feeders are equipped with series current-limiting reactors. In the event that the NSTAR system and the generator are both operating in parallel, the reactors are in service and limit the short-circuit current at the 13.8 kV bus.

SBPC Switching Station

The 115 kV/13.8 kV transformers and the 13.8 kV MBTA combustion turbine generator supply power to the 13.8 kV distribution system via a four-bus switchgear arrangement, configured as a normally closed ring-bus. The transformers, bus-ties, and feeder circuit breakers are equipped with full protective relaying, as well as local and remote control capabilities.

The SBPC switching station modes of operation are summarized in Table 1.

NSTAR System	115 kV/13.8 kV Transformers	Generator	Generator Feeder Reactors	13.8 kV Bus Arrangement
Both Sources In-Service	In-Service	Out-of-Service	Out-of-Service	Ring Bus
Both Sources In-Service	In-Service	In-Service	In-Service	Split Bus
One Source In-Service	In-Service	Out-of-Service	Out-of-Service	Ring Bus
Both Sources Out-of-Service	Out-of-Service	In-Service	Out-of-Service	Ring Bus

Table 1 - The SBPC Switching Station Operation

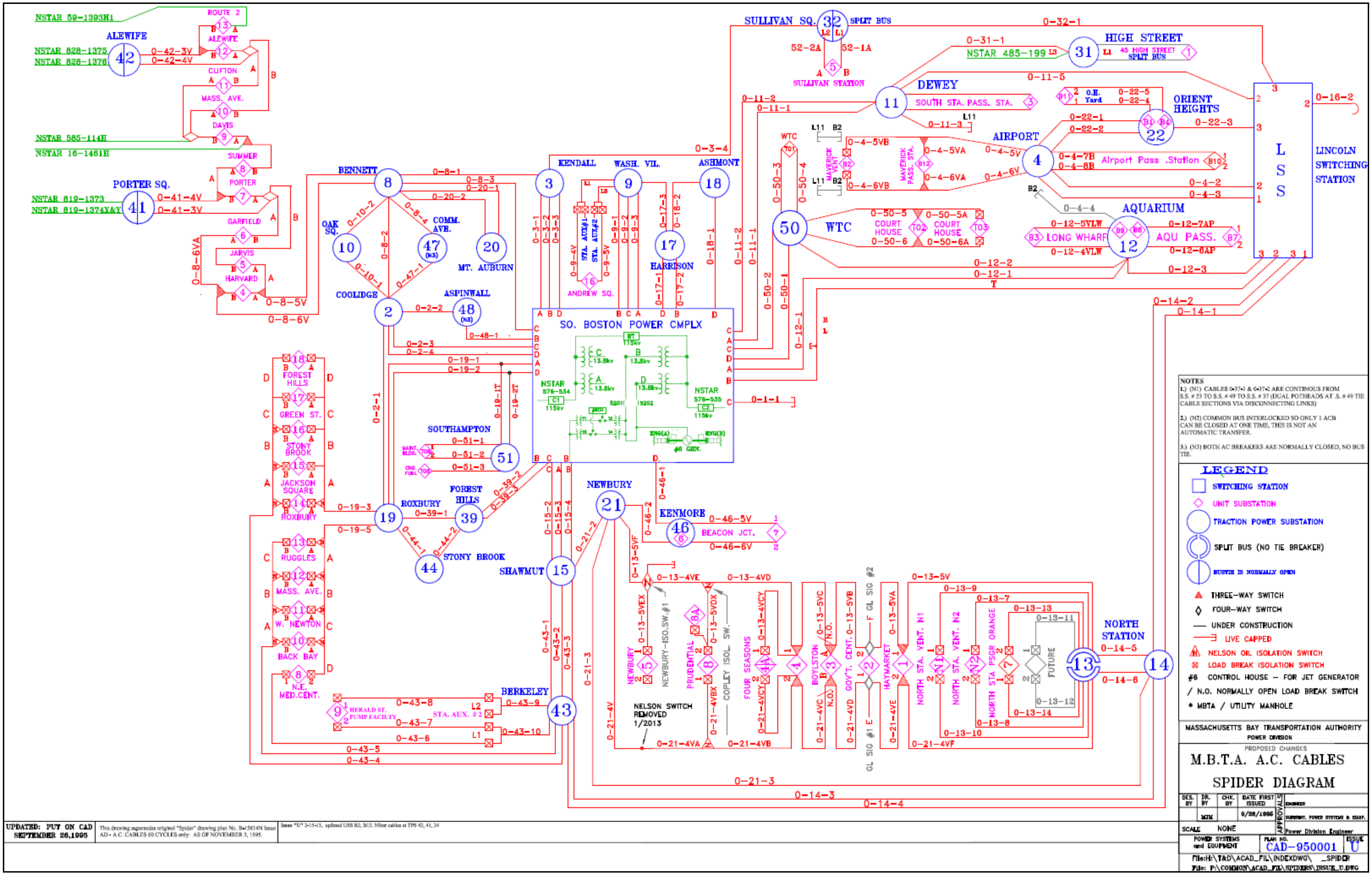
13.8 kV Distribution Network

Lincoln Switching Station (LSS)

The Lincoln Switching Station shown in Figure 2 is comprised of three-buses and 13.8 kV switchgear with two bus-tie circuit breakers. Both bus-tie circuit breakers are normally closed. LSS is an interconnection point for substations and SBPC.

Feeder Distribution System

The MBTA's 13.8 kV power supply system is a complex network of medium voltage distribution cables where multiple load and short-circuit current paths are possible, depending on the system configuration.



NOTES

1.) (N1) CABLES 0-37-1 & 0-37-2 ARE CONTINOUS FROM S.S. # 23 TO S.S. # 49 TO S.S. # 37 (DUAL POTHEADS AT .S. # 49 TIE CABLE SECTIONS VIA DISCONNECTING LINKS)

2.) (N2) COMMON BUS INTERLOCKED SO ONLY 1 ACB CAN BE CLOSED AT ONE TIME, THIS IS NOT AN AUTOMATIC TRANSFER.

3.) (N3) BOTH AC BREAKERS ARE NORMALLY CLOSED, NO BUS TIE.

LEGEND

- ☐ SWITCHING STATION
- ◇ UNIT SUBSTATION
- ○ TRACTION POWER SUBSTATION
- SPLIT BUS (NO TIE BREAKER)
- BUSTIE IS NORMALLY OPEN
- ▲ THREE-WAY SWITCH
- ◇ FOUR-WAY SWITCH
- — UNDER CONSTRUCTION
- LIVE CAPPED
- NELSON OIL ISOLATION SWITCH
- ☒ LOAD BREAK ISOLATION SWITCH
- #6 CONTROL HOUSE – FOR JET GENERATOR
- / N.O. NORMALLY OPEN LOAD BREAK SWITCH
- • MBTA / UTILITY MANHOLE

MASSACHUSETTS BAY TRANSPORTATION AUTHORITY
POWER DIVISION

PROPOSED CHANGES

M.B.T.A. A.C. CABLES
SPIDER DIAGRAM

DES. BY	DR. BY	CHK. BY	DATE FIRST ISSUED	APPROVALS
	MTM		9/26/1995	ENGINEER SUPERINT. POWER SYSTEMS & EQUIP. Power Division Engineer

SCALE NONE

POWER SYSTEMS and EQUIPMENT
PLAN NO. CAD-950001
ISSUE U

File:H:\T&D\ACAD_FIL\INDEXDWG\ _SPIDER
File: P:\COMMON\ACAD_FIL\SPIDERS\ISSUE_U.DWG

UPDATED: PUT ON CAD SEPTEMBER 26,1995

This drawing supersedes original "Spider" drawing plan No. B-15814N Issue AD - A.C. CABLES 60 CYCLES only: AS OF NOVEMBER 3, 1995.

Issue "U" 2-15-13, updated USS B2, B12. NStar cables at TPS 42, 41, 24

Figure 2: MBTA AC Cables Spider Diagram

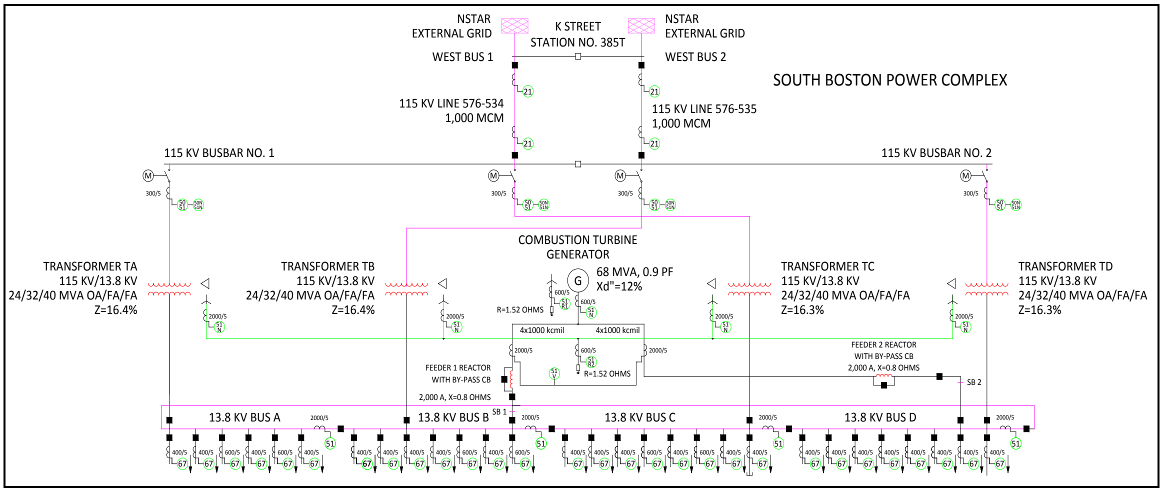


Figure 3: South Boston Power Complex

The distribution network consists of 15 kV Paper-Insulated Lead-Covered (PILC) shielded copper, three-conductor cable feeders namely:

- 2/0 AWG cables - aerial
- 4/0 AWG cables - ductbank system
- 600 kcmil cables - ductbank system
- 1,000 kcmil cables - ductbank system

The feeders distribute power from the SBPC 13.8 kV switching station bus to the traction power substations, unit substations and LSS. In addition to the multiple 13.8 kV feeder cables from SBPC and LSS, there are radial feeders to the traction power substations and backup power supply is provided by substation-to-substation cross feeders.

The distribution system is essentially comprised of numerous feeder loops, where each feeder loop supplies several traction power substations with one or multiple feeder cables. The meshed nature of the system results in a reliable system network, as there generally are multiple paths to supply substation loads in the event of a cable failure or contingency outage.

Traction Power Substations

The 13.8 kV ac distribution system supplies power primarily to 26 TPSS. Each TPSS has an ac switchgear line up that is connected by two or more ac distribution feeders as illustrated in Figure 4. The TPSS ac bus also serves the needs of unit substations. In the spider diagram, High Street TPSS receives power from both the MBTA's ac distribution system and NSTAR; under normal operation, the bus tie breaker is open. The TPSS and unit substations from Porter Square to Alewife are fed primarily by NSTAR distribution feeders.

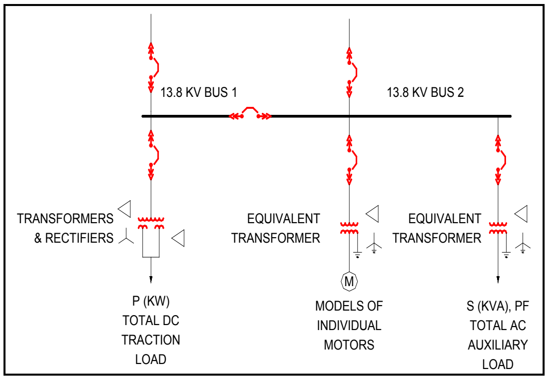


Figure 4: Substation Configuration

Unit Substations

The unit substations distribute power at 480 V. Unit substations supply power to many types of loads including tunnel ventilation fan motors, pumping stations motors, and various auxiliary power systems, such as passenger station loads, signal house loads, and maintenance facilities.

STUDY METHODOLOGY

The comprehensive ac and dc analysis study being undertaken incorporates the contribution of each sub-system that influences the overall system behavior under normal operation and short-circuit cases; the process is illustrated in Figure 5. The objective of the study is to ensure that the system operates satisfactorily under normal operating conditions and system outages, while supplying the increased power demand resulting from increases in revenue service and short-circuit levels at NSTAR.

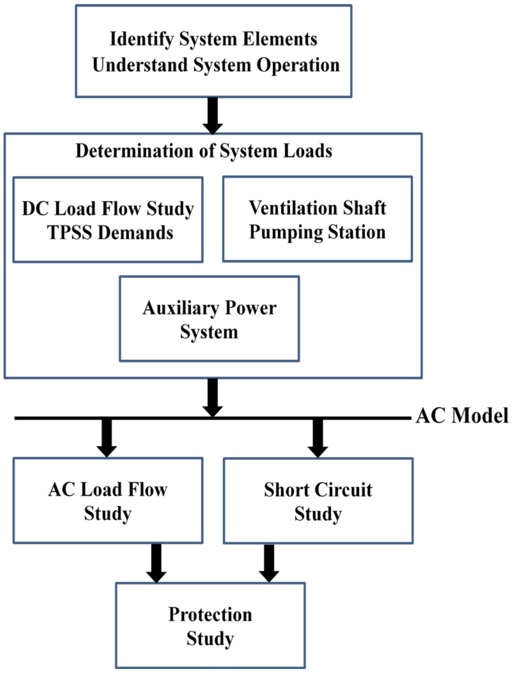


Figure 5: System Development Procedure Flowchart

Identify System Elements &Understand System Operation

In developing a computer model, it is important to identify the different elements of the power system, understand their operational behavior and interaction within the system network. The system operational characteristics are essential in defining simulation scenarios for the various studies.

Determination of System Loads

DC Load Flow Study - TPSS Demands

The traction power system loads fluctuate highly as shown in Figure 6. This is the result of abrupt, impulse-like changes in the power requirements of trains, as they accelerate, decelerate, or as they encounter or leave track grades and other civil elements. The magnitude and frequency of the train power requirements increase during peak periods of operation.

The following transit lines are part of the MBTA ac distribution network:

- Rapid Transit System (Heavy Rail)
  - Red Line
  - Blue Line
  - Orange Line
- Light Rail System
  - Green Line (includes B, C, D & E Lines)
  - Mattapan Line
- Electric Trolley Bus System
  - Silver Line
  - Electric Trolley Bus Service in Belmont, Cambridge and Watertown.

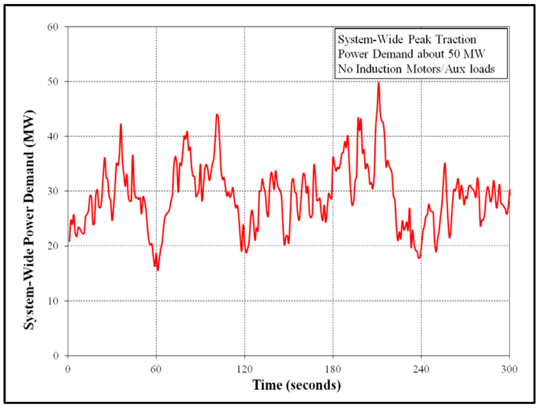


Figure 6: Combined System Traction Power Demand

The dc traction power system loads are being determined by building models of all the transit lines in a single database and running schedule scenarios which represent the expected loading of the traction power system using TrainOps® simulation software.

The advantages of this approach are:

- Identification of peak loads in the rapidly variable load profile of each substation.
- Capture possible future load increases due to train service operations and schedule enhancements.
- Capture combined load demand for substations on the system that provide power to more than one transit line.
- Effectively present coincident, non-coincident and variable loads.

The simulations capture the traction power substation loads during the peak period of operation. The peak values are obtained in one second intervals. Substation loads can be expressed as coincident, non-coincident, or variable.

During normal system operation, the peak loads occur at different times. Summarizing all the TPSS peak loads on the system is referred to as the non-coincident load. Using non-coincident loads is considered an unrealistic and overly conservative assumption since these are the peak values that occur at different times. In addition, the sum of all the non-coincident loads in the system will be significantly higher than the sum of the coincident loads.

Understanding how much load is present at any given time is referred to as the coincident load. The coincident load is what the ac distribution system will see as a maximum at any given time.

The coincident loads are realistic and utilized as an input to the ac model. For coincident load determination, the individual TPSS loads are based at the time when the entire system load is peak. The coincident and non-coincident loads are compared in Figure 7. In Figure 7 the total coincident and non-coincident loads are 50 MW and 105 MW, respectively.

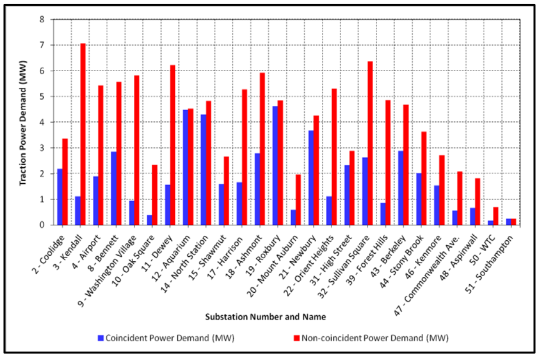


Figure 7: Coincident and Non-coincident Loads

Variable loads (time-varying loads) represent the most realistic loading profile. Variable loads are particularly suitable for the evaluation of loading levels of equipment such as generators, transformers, cables and estimation of the time duration a particular type of equipment may be overloaded. The generator power demand under particularly onerous conditions, when supplying the traction power loads, ventilation fan motors and pump motors, is illustrated in Figure 8. The diagram also shows the base, peak, and emergency ratings of the gas turbines for comparison.

In "DIgSILENT PowerFactory" (ac software), this type of simulation is called quasi-dynamic simulation. It has the ability to represent loads as a time-varying function, rather than a single value. This is particularly advantageous when representing traction power loads, as the load in each substation varies independently with time. The individual substation time-varying loads are obtained from the DC load flow simulation of the system and are entered into the software as power versus time characteristics.

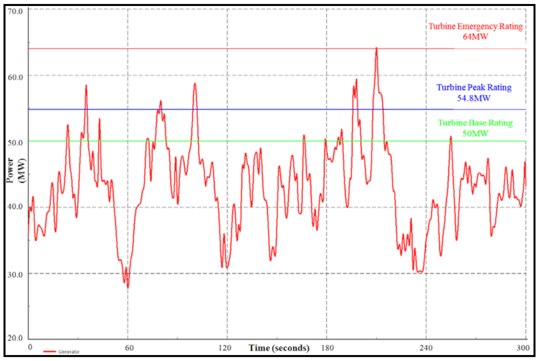


Figure 8: Generator Supplying Demand of Entire System

Ventilation Shaft and Pumping Station

The ventilation shaft and pumping station loads are being determined by collecting the fan motor, pump motor and transformer ratings. The ventilation shaft and pumping station motors in each facility are represented by an equivalent circuit of each induction motor. The individual induction motors are connected to an equivalent transformer that is connected to the 13.8 kV busbars.

During normal operation, each motor exerts a load on the system. In the case of short circuit, the motors operate as a source of current to the short circuit. The contribution to the short circuit is typically for a few cycles until the rotor flux reduces to zero.

In determining loads to be used in the load-flow study, it is important to review the frequency of operation of the various fan and pump motors based on either historical data or standard operation procedures of equipment. Alternatively, all motors can be included for the worst case loading situation.

Auxiliary Power System

The auxiliary power system loads are being determined by collecting the auxiliary power demands in the substations, and are expressed as the real power demand (kW) and related power factor. The individual auxiliary system loads are lumped and supplied via an equivalent transformer connected to the 13.8 kV busbars.

There are two types of loads, intermittent and continuous. With intermittent loads, such as elevators, loading occurs at various irregular intervals. These types of loads are generally not included. Continuous loads are loads that are always in operation, such as signal loads, station loads including lighting, concessionaire stores, and escalators. The continuous loads are generally included in the model.

AC Load Flow Study

The load-flow studies calculations are being conducted for the following purposes:

- Calculate load currents in all cables and circuit breakers; confirm that ampacities of cables and the continuous current ratings of circuit breakers are not exceeded.
- Identify cables and circuit breakers where ampacity or continuous current rating is nearing its rating or exceeding it.
- Calculate voltage values for all buses in the system and verify bus voltage levels do not violate the established study criterion.
- Identify buses with voltage values below minimums established in the study criterion.
- Check the settings of instantaneous elements of directional feeder relays. In the event of high load transfer associated with opening and closing of circuit breakers under load, a polarization error may occur causing the relay to operate unintentionally.

A typical power utility system study takes into consideration the performance of the system under both normal operating conditions, when all equipment is in service, and operation under a single contingency condition, when a single item of equipment is out of service. A typical single item out of service may be a cable feeder, a transformer or any distribution system element.

In the case of a transit system, a more strict study criterion should be applied rather than what is normally applied to a typical utility system since a significant portion of the transit system is underground and elevated. Furthermore, power outages could represent a public safety issue to passengers. A combination of single and double contingency outage simulations are being used for the load-flow study. This will allow for the possibility of a fault occurring while another item of equipment has been switched out of service for repair or maintenance. The system under "single contingency" and "double contingency" conditions should operate normally; that is, the system equipment loadings should be within the equipment's ratings, and the substation bus voltages should remain above the minimum acceptable value.

In this context, normal equipment operation is defined as follows:

- The maximum load current should not exceed the feeder ampacity, circuit breaker continuous rating, or transformer rated current.
- The voltage level at any substation bus should not fall below 95% of nominal voltage.

AC Load Flow Study - Schedule of Studies

The following studies are being performed:

- All Systems in Service. The system is simulated under normal operating conditions with all systems in service. This will become the "base case," serving as the system reference when evaluating the subsequent contingency simulations. Two alternative base configurations are considered:
  - Primary feed from the NSTAR system
  - Primary feed from the MBTA combustion turbine generator
- Systems Contingency Conditions. The contingency simulations allow one to investigate the system performance under equipment outage conditions, including:
  - SBPC 115 kV/13.8 kV transformer outage
  - Various distribution feeder cable outages (single and double contingencies)

The contingency studies are specifically selected to produce the highest feeder loading and/or the lowest bus voltage using the following considerations (incremental steps):

- Outage of the heaviest-loaded feeder in order to break the highest supply source to a substation or a loop.
- Outage of the next heaviest-loaded feeder to create even higher loading on the heaviest-loaded feeder.
- Outage of a feeder supplying a bus with an already marginal voltage level to cause an even lower voltage condition on the bus.

Short-Circuit Study

The short-circuit studies are being performed for the following reasons:

- Verify that the interrupting and momentary (close and latch) current ratings of the circuit breakers are not exceeded, as well as identify circuit breakers where the short-circuit duties are at or near their ratings.

- Use the various scenarios to calculate the maximum and minimum short-circuit current levels for relay coordination purposes. The maximum momentary r.m.s current and the 30-cycle current are used to set instantaneous and over current relays, respectively.

Circuit breaker evaluations are determined as recommended by the ANSI/IEEE C37.04, .06, .010 series of standards.

Short-Circuit Study - Schedule of Studies

The short-circuit types considered are three-phase, phase-to-phase and phase-to-ground. The purpose of the short-circuit studies is to:

- Determine the maximum short-circuit currents under the appropriate system operating conditions with all circuits in service and under single contingency conditions with maximum short-circuit current infeed out of service. Infeed is the current contribution to a fault made by sources, lines, transformers and generators.
- Determine the minimum short-circuit currents under normal system operating conditions with all circuits in service.

The three types of faults used to set relays are:

  - Three-phase faults to set phase fault relay settings
  - Phase-to-phase faults to set Δ-GY connected transformer phase-fault relay settings
  - Phase-to-ground faults to set ground-fault relay settings

The three-phase and phase-to-ground short-circuit studies are being performed to establish the highest short-circuit current flow through a particular element of protected equipment, as the fastest relay operation occurs at the highest current. The following are used to obtain the highest short-circuit current in the equipment:

- Simulation of equipment which contributes the maximum short-circuit current to the fault or the "maximum infeed" being out-of-service.
- In a loop circuit, opening the loop at one end by a circuit breaker.

In compliance with the ANSI C37-approved method, all short-circuit studies are performed with unity pre-fault voltage and zero short-circuit impedance.

Protective Relay Setting Study

The protective system includes both bi-directional and directional over-current relays of various characteristics. The majority of the relays are electro-mechanical; however, the newer substations use modern, solid-state microprocessor-based multifunction relays.

Rectifier Transformer Protection

The phase-fault and ground-fault relays protect the rectifier transformers from overload, phase-fault, and ground-fault short-circuit current conditions and provide backup protection to the dc distribution system protective relays downstream. Therefore, the rectifier transformer primary winding relays need to be set and time-coordinated with the dc relays. In addition, the rectifier transformer relays need to coordinate with the rectifier diode fuses.

To develop the rectifier transformer protective relay settings, the following data should be depicted on the protective relay coordination chart:

- Rectifier transformer and its associated rectifier full load current.
- Rectifier transformer and its associated rectifier overload characteristic.
- Rectifier transformer damage curve.
- Rectifier transformer inrush current.
- Rectifier single diode leg and combined diode legs fuse characteristics.

The protective relay settings should be chosen to achieve the following:

- Allow flow of the transformer inrush current upon energization, typically eight-to-ten times the full load current, lasting for approximately 0.1 seconds.
- Protect the rectifier transformer and its associated rectifier against overload currents taking into account the transformer overload characteristic.
- Protect the transformer against damage, taking into account the transformer damage curve.
- Allow fuse operation for rectifier internal faults.
- Clear the transformer following internal faults.

Feeder & Bus Tie Protection

For the feeder directional relays with their operating direction pointing to SBPC, their overcurrent settings can be set low since the power flow is from SBPC, which is in the non-operating direction of these relays and, as a result, these relays will not be sensitive to loads. The relays along the loops will be set to coordinate with these relays.

The feeder directional relays need to be set as they relate to each loop. Typically, the loop is broken at one end by opening a circuit breaker and the relays are set around the loop, away from the opened circuit breaker. Then, the open circuit breaker is closed, and the circuit breaker at the other end of the loop is opened and the process is repeated. A typical loop is shown in Figure 9.

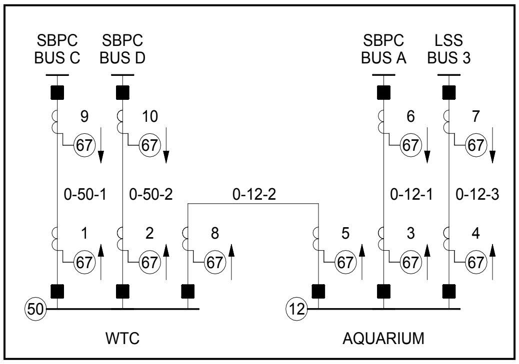


Figure 9: World Trade Center Substation (WTC) Loop Relays, Feeders and Substations

The feeder phase-fault (67) and ground-fault relays (67N) protect the substation-to-substation feeders and substation-to-substation cross-feeders from overload, phase-fault and ground-fault short-circuit current conditions and provide backup protection to the feeder and substation protective relays downstream.

The feeder protective relay settings should be chosen to achieve the following:

- Allow for the feeder "cold load" pickup upon cable circuit power restoration after a lengthy outage.
- Protect the feeder against damage. The relay characteristic curve should be set below the intermediate overload and short-circuit damage curves of the cable.
- Clear the feeder on internal faults.
- Allow coordination with the slowest-operating relay at the downstream substation.

The phase-fault and ground-fault bus-tie relays at SBPC provide backup protection for the bus outgoing relays. The bus-tie protective relay should coordinate with the slowest bus outgoing feeder relay.

115 kV/13.8 kV Transformer Relay Settings

The phase-fault and ground-fault relays protect the transformers from excessive overloads, as well as phase-fault and ground-fault short-circuit conditions.

These transformers will have settings based on conditions similar to other transformers in the system; therefore, the protective relay settings should be chosen to achieve the following:

- Allow flow of the transformer inrush current upon energization, typically eight-to-ten times the full load current, lasting for approximately 0.1 seconds.
- Protect the transformer against overload currents as specified by the transformer overload characteristic.
- Protect the transformer against damage, taking into account the transformer damage curve.
- Clear the transformer following internal faults.

Generator Relay Settings

The phase-fault and ground-fault overcurrent relays protect the combustion turbine generator from excessive overload, phase-fault and ground-fault short-circuit conditions. In general, a simple time-overcurrent relay cannot be set to provide adequate backup protection. A steady-state fault current for a three-phase fault may result in generator current magnitudes less than the full-load current of the generator; however, the fault will cause the generator terminal voltage to drop significantly. In order for an overcurrent relay to detect and operate on uncleared system faults, two types of phase-fault overcurrent relays are used:

- Voltage-controlled relays- The voltage-controlled (51/27C) feature allows the relay to be set below the rated current, and the operation is blocked (inhibited) until the voltage falls below the pre-set voltage.
- Voltage-restrained relays- The voltage-restrained (51/27R) feature causes the pick-up value to decrease with reducing voltage.

Both types of relays are designed to restrain operation under emergency overload conditions and still provide adequate sensitivity for the detection of faults.

Sequence of Relay Settings

The aforementioned protective relay settings philosophy was developed for the study for all relays in the MBTA system, including feeder relays, bus-tie relays, transformer relays, and generator relays.

The heavily interconnected MBTA network configuration may be considered as a combination of distinctive radial feeder connections and feeder loops. The following general procedure is followed in the protective relay settings:

- The loops are set first.
- Once all loop relays are set, each bus-tie relay is set to coordinate with the slowest relay on either bus section of the bus-tie.
- Finally, the SBPC transformer relays and the generator relays are set to coordinate with the slowest bus-tie relay.

The above procedure is the generally accepted method for relay setting. However, on a cautionary note, in an extensively interconnected network such as the MBTA's, there may be occasions, such as multiple feeder outage scenarios, where "ideal" relay coordination may not be achieved and a compromise may be necessary. In these circumstances, the preferred alternative will depend on the necessary personnel protection, equipment damage and the effect on the system operation.

CONCLUSION – POTENTIAL APPLICABILITY TO OTHER TRANSIT SYSTEMS

Transit systems are considered critical infrastructure. During the Northeast Blackout of 1965, the MBTA was the only system operating on the entire East coast [8]. Some transit agencies, such as NJ Transit, have commenced studies into building a more resilient system to minimize crippling effects, such as the one caused by Superstorm Sandy. "The State of New Jersey is collaborating with the U.S. Department of Energy to design NJ TransitGrid - a first-of-its-kind electrical microgrid capable of supplying highly-reliable power during storms or other times when the traditional centralized grid is compromised" [9]. As ac/dc transit agencies consider microgrid installations and existing ac distribution systems experience load growth or system changes, the collaborative approach in analyzing both transit power demands into the ac systems when performing load-flow, short-circuit and protective relay device coordination studies as outlined in this paper is recommended. In addition, this approach is also suitable for evaluation of the impact of traction loads on power utility systems.

SOFTWARE TOOLS

TrainOps®. The dc traction power system loads are being calculated using the LTK-developed TrainOps® software. TrainOps® is a comprehensive, state-of-the-art train operations and electrification system modeling and simulation software.

The software models the entire traction electrification system, including the impedance of the power supply utility system, traction power substations, and the traction power distribution and return systems. The power distribution and return systems are modeled separately, enabling representation of multiple power distribution conductors; i.e., parallel cables, and return system bonding and cross bonding.

The software computes the essential values of the traction power system using parameters of the system operation, including train and running rail voltage profiles along the alignment, distribution system currents, catenary and third rail conductor operating temperatures, substation power demands, and substation energy consumptions. The software models the full interaction between the system and associated train voltage variation with the rolling stock performance.

PowerFactory. PowerFactory software by DIgSILENT is being used for the ac load-flow and short-circuit studies. The software is capable of modeling 1-, 2-, and 3-wire ac networks with neutrals, grounding conductors, and dc networks. The networks can be mesh or radial of any complexity, balanced or unbalanced, including harmonics.

In addition to standard power devices, the software can also represent special equipment, such as Static VAr compensators (SVCs), rectifiers, wind generators, fuel cells, and energy storage devices.

REFERENCES

1. Westinghouse Electric Corporation, **Electrical Transmission and Distribution Reference Book**, Fourth Edition: Eighth Printing, 1964.
2. Southwire Company, **Power Cable Manual**, 4th Edition, 2005.
3. Okonite Company, **Engineering Handbook**, 3/2011**.**
4. IEEE Std. 242, **IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (Buff Book)**
5. IEEE Std. 399, **IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (Brown Book)**
6. IEEE Std. 551, **Calculating Short-Circuit Currents in Industrial and Commercial Power Systems (Violet Book)**
7. IEEE Std. C37.04, .06, .010, **High Voltage Circuit Breaker Rating**
8. Boston Sites and Insights: An Essential Guide to Historic Landmarks In and Around Boston by Susan Wilson
9. https://www.njtransit.com/tm/tm_servlet.srv?hdnPageAction=PressReleaseTo&PRESS_RELEASE_ID=2884

ABOUT THE AUTHORS

Richard N. Rauceo is a staff consultant specializing in traction power systems with LTK Engineering Services based in the Boston, Massachusetts office. He holds a Bachelor's degree in Electrical Engineering from Drexel University and Master's of Science degree in Systems Engineering from Missouri University of Science and Technology. Richard has over 6 years of experience in traction electrification systems. Richard has worked extensively in traction power design and construction-related services. He is an expert in traction power system simulation and modeling of ac and dc power systems for light rail, streetcar, electric trolley bus, rapid transit and commuter rail systems.

Tristan A. Kneschke is a senior electrical engineer with LTK Engineering Services, a rail transit consulting firm headquartered in Ambler, Pennsylvania. He holds B.Sc. and Ph.D. degrees in Electrical Engineering from University of Sussex, UK. Over his 25-year association with LTK, Tristan has participated in more than 100 assignments of varying complexities and durations. The projects included system studies, preliminary designs, final designs, and construction-related services. His main areas of interest include modeling and simulation of ac- and dc-powered transportation systems, investigation of electrification impact on power utility transmission and distribution systems, application of protective relay settings, and energy storage device applications.

Michael K. Fitzgerald is a Project Manager with the Massachusetts Bay Transportation Authority. Over his 5½ years with the Authority, Michael has held the positions of Deputy Director of Power and Superintendent of Transmission and Distribution. In addition to his responsibilities of directing a large workforce to maintain and repair the Power Network, he also oversaw the implementation of the $200 million Capital Improvement Program for the Power Systems Maintenance Division. In Michael's current position, he has oversight of the Orange Line Traction Power Substation Upgrades, South Boston Switching Station Jet Control Upgrade, South Boston Switching Station 24/32/40 MVA Transformer replacement and the ac Power Load Flow Study. Prior to joining the MBTA, Michael held supervisory positions for 8 years in the Power and Operations Departments at Verizon Communications. Michael holds a Bachelor's degree in Electrical Engineering from the University of Massachusetts Lowell, and a Master's degree in Administrative Studies from Boston College.

John A. Martin is currently the Director of the Power Systems Maintenance Division of the MBTA in Boston, Massachusetts. He has over 30 years experience in electrical construction and generation. John is a 19 year veteran of the MBTA Power Division with expertise in electrical maintenance and construction, and has held positions of electrician, foreperson, and project manager. John is a veteran of the United States Air Force who has worked as project lead on power plant installations, turbine overhauls, radar and navigation systems, and antennae units.