Part 12

Traction Power Supply and Distribution Requirements for DC Rail Transportation Systems

—2011—

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SECTION 12.1 - INTRODUCTION

12.1.1 SCOPE AND PURPOSE

Part 12 of Chapter 33 provides guidelines and recommendations for the planning and design of modern electrified rail transportation systems that employ direct current (dc) for traction power. These electrified rail systems are normally categorized as Light Rail Transit (LRT) and Heavy Rail Transit (HRT). Electric Trolleybus (ETB) and some Automated Guideway Transit (AGT) and Automated People Mover (APM) systems also employ dc power for propulsion, but are not specifically addressed herein. Most of the system planning and design guidelines, and the recommendations for LRT and HRT, however, will also apply to ETB and dc APM systems.

Traction power requirements for historic trolley systems are included under the LRT system category in this chapter, and dc commuter rail systems are included under the HRT category. The purpose of these guidelines and recommendations is to standardize the planning and design of these systems based on proven, industry-accepted practices.

Voltage levels are covered in Part 3 of this chapter; a glossary of terms and list of abbreviations is located in the Glossary.

SECTION 12.2 - DC TRACTION POWER SYSTEM CHARACTERISTICS

12.2.1 LIGHT AND HEAVY RAIL SYSTEM DEFINING CHARACTERISTICS

a. Light rail transit (LRT) is comprised of passenger rail cars operating as single car units or in consists of up multiple cars. Light rail is suited for street running type operations in which the LRT trains obey roadway traffic signals along with motorists, as well as operation on semi-exclusive or exclusive ROW. Roadway traffic signal priority or preemption can be established with local transportation authorities to enhance train operations. Power for light rail transit is usually supplied by an overhead contact system and collected through a pantograph on the car; a trolley pole is used instead of a pantograph on some long-established street-running LRT systems. LRT is also known as "streetcar", "tramway" or "trolley car."

b. Heavy rail transit (HRT) is an electric railway with the capacity for a heavy volume of traffic. It is characterized by: high speed and rapid acceleration passenger rail cars operating singly or in multi-car trains; separate rights-of-way from which all other vehicular and foot traffic are excluded; sophisticated signaling; and, high level platform loading. If the service were converted to full automation with no onboard personnel, the service would be considered an automated guideway. HRT is also known as “metro”, “subway”, “rapid transit” or “rapid rail”. DC power for heavy rail transit is typically supplied by third rail (“contact rail”) and collected on the vehicle through collector shoes or paddles which ride on top of, or underneath, the third rail; however, it may also be supplied by an overhead contact system (OCS) via pantographs.

c. The traction power system should be designed to use proven hardware and design concepts. The systems fixed facilities (structures and buildings) should be designed for continued operation over a minimum period of 50 years. Major fixed system equipment should be designed for a minimum lifetime of 30 years.

d. Major equipment should be supplied by established manufacturers, have a documented history of successful operation, and be available “off the shelf”, as far as practicable. The same requirements should apply to spare parts.

e. Recommended voltage levels for LRT and HRT systems are provided in Part 3. The typical nominal voltage for new LRT and HRT systems in North America is 750 Vdc. Some newer LRT systems with high passenger capacity requirements and/or the need for increased distances between substations have adopted 1,500 Vdc nominal.

12.2.2 TRANSIT VEHICLE PROPULSION METHODS

a. DC rail transit vehicles are typically propelled by one of four methods: Cam-controlled dc motors, chopper-controlled dc motors, linear induction motors, or converter-controlled ac induction motors. Converter-controlled ac induction motor propulsion, commonly referred to as an “ac traction drive” or “ac propulsion”, is the most common propulsion method employed for new LRT or HRT rolling stock at this time.

b. For propulsion systems employing cam-controlled dc traction motors, series type dc motors have been most commonly used. Speed control for series dc motors is obtained at lower speeds by varying the terminal voltage of the motor through the switching in and out of resistors, and by reconfiguring the motors in a car from series to parallel operation. At speeds above motor base speed, the motor fields are shunted ("weakened") to obtain greater speeds. Regeneration of power from the car into the traction power system during braking (regenerative braking) is not possible with this older propulsion system technology.

c. Chopper-controlled dc propulsion behaves similarly to cam-controlled dc motors, except that the chopper provides the voltage control rather than the switched resistors. If separately excited dc motors are used instead of series dc motors, regenerative braking is possible.

d. Linear induction motor propulsion systems used in rapid transit systems to date have employed the "short stator" type design, with the induction motor primary located on the car, and a reaction rail or plate on the guideway; a contact rail is used to provide dc power supply to the car. Motor speed control is provided by variable voltage, variable frequency converters. This form of propulsion has been used in North America on such systems as the JF Kennedy Airport AirTrain, the TTC Scarborough LRT, the Vancouver Skytrain, and the Detroit People Mover.

e. AC propulsion systems employ power electronics to convert dc traction power to variable voltage, variable frequency ac input to 3-phase induction motors. AC propulsion systems typically provide regenerative braking capability. Modern ac propulsion systems also offer forced reduced performance (FRP) capability, which enables a proportional reduction in propulsion motor current (and tractive effort) when contact system voltage drops below a programmable threshold. Vehicles equipped with FRP are therefore more tolerant of low contact system voltage, reducing their acceleration rates (and propulsion system current demand) in response to low contact system voltage, as long as the voltage remains above the design drop-out limit.

12.2.3 TRANSIT VEHICLE POWER REQUIREMENTS

a. Transit vehicle power requirements vary greatly as vehicles accelerate from standstill to a constant speed, as they operate at constant speed, and as they brake from constant speed to a standstill. Vehicle propulsion power requirements at a particular speed are a function of many factors that include: vehicle dimensions and empty weight; passenger load; track curvature and gradient, propulsion system type, efficiency and tractive effort vs. speed characteristics; and contact system voltage.

b. At standstill, vehicle power requirements consist of vehicle "auxiliaries" only, which include the power required to operate HVAC systems, lighting, air compressors, battery chargers, and miscellaneous electronics. Some of the equipment that comprises the auxiliary load operates continuously, some cyclically, and some cyclically and seasonally. For this reason, vehicle auxiliary load is difficult to estimate by calculation alone; measurements taken over a period of time are preferable to calculation when a reliable per-car value is needed.

c. While in motion, a transit vehicle’s power requirements consist of propulsion system plus auxiliary system loads. For dc transit vehicles, this power requirement is most conveniently expressed in terms of Amperes, or amps, at line voltage. During full acceleration, the peak current demand of a single LRT or HRT vehicle can be on the order of 1,500 amps at 750 Vdc. Peak current demand can be predicted from design or test data curves prepared by the vehicle manufacturer; however, these curves are normally prepared for one specific set of test track conditions (level tangent track, typically), and may not adequately reflect operation everywhere on the system. Measurements of current demand obtained during actual operation of a vehicle on its own system provide the most reliable results. Alternatively, computer simulation can be used to predict vehicle power requirements and performance; it is recommended that simulation results be corroborated against manufacturer or measured performance data if these are available.

d. Transit vehicles equipped with regenerative braking can return propulsion power to the contact system, minus the power required for vehicle auxiliary loads and dynamic braking. The amount of power returned depends on the availability of power “receptors” (electrical loads); these receptors are typically nearby trains, but they can also be energy storage devices. At present, the return of regenerated power to the electric utility, which requires bi-directional (4-quadrant) substation converters for dc traction power systems, is not yet common in North America. Regenerative braking can be a source of considerable energy savings, depending on system configuration.

12.2.4 TRACTION POWER SYSTEM LOAD CHARACTERISTICS

a. In comparison with other types of power systems, traction power systems are very dynamic in behavior. Not only do the major electrical loads in a traction power system vary significantly with time, but they also physically move between substations. The total load supplied by a traction power substation is thus time-varying (varying from moment to moment), as are the loads at adjacent substations.

b. To provide a basis for the selection and sizing of traction power equipment such as transformers, rectifiers, switchgear and cables, the varying load currents are converted to equivalent constant values. For most equipment, a root-mean-square (rms) calculation is performed for this purpose (An rms calculation produces an equivalent constant value of current from any periodic, time-varying current waveform; the rms value of a periodic current waveform is defined as the equivalent constant direct current which would cause the same average heating in a resistive element).

c. Utilities that supply electricity to transit systems typically have separate charges for energy consumption (kWh) and for peak demand (kW or kVA). Demand is an average of instantaneous power measured over a period of time termed the “demand interval”; demand intervals are typically 15 or 30 minutes. Peak demand is the highest demand measured during a billing period.

d. Transit systems that increase the frequency and/or the lengths of trains during rush hour will have a daily system load characteristic (load versus time graph) that peaks twice daily, one peak for the AM rush hour and one for the PM rush hour. This traditional transit system load shape is characteristic of individual main line substations as well; yard substations, however, typically have different load characteristics that are functions of train storage procedures. The AM and PM peak period loads for main line substations are typically much higher than the non-peak period loads. In electric utility supply terms, these systems have low load factors. Load factor is defined as the average load over a specific time interval divided by the peak load (demand) occurring during the same interval [1]. For utility supply and equipment rating purposes, the time interval utilized is typically a 24 hour day, resulting in the term "daily load factor". A sampling of heavy/commuter rail and light rail systems has found average daily load factors of 0.50 and 0.60, respectively [2].

e. The type of demand billing used by electric utilities can have a significant impact on transit system power costs. The most advantageous arrangement is for all traction power substations to be treated as a single load for peak demand billing purposes (also known as coincident or conjunctive demand billing), using the longest demand interval available. Otherwise, in the event of a serious catch-up service scenario, new peak demands could be reached at each substation involved in the scenario, even though the total system load remains the same during the event. If the utility also charges for the highest peak demand achieved at each substation over the course of the previous 6 to 12 months (also known as a “demand ratchet”), then the power cost penalty at each substation for a catch-up service event could be repeated for many months. There is significant precedent among existing transit properties for negotiating longer peak demand intervals and coincident or conjunctive demand billing with their supplying utilities, which offers the potential for significant operating cost savings.

f. DC traction power systems utilizing controlled (thyristor) and uncontrolled (diode) rectifiers are potential sources of voltage and current harmonic distortion for the supplying electric utility(s), similar to large motor drives and UPS systems. Proper system design including compliance with IEEE Standard 519, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, will normally preclude power quality issues with the supplying utilities.

g. Because of their unique load characteristics relative to other utility customers, it is recommended that transit agencies begin electricity supply and rate negotiations with electric utilities as early as possible in the planning and design of new HRT or LRT facilities.

SECTION 12.3 - DC TRACTION POWER SUBSTATIONS

12.3.1 SUBSTATION TYPES AND CONFIGURATIONS

a. DC traction power substations convert (“rectify”) three-phase alternating current (ac) to direct current (dc) for utilization by rail vehicles. With the exception of some trolley systems, the ac supply is in the medium voltage range, 4.16 to 34.5 kV being typical. The conversion from ac to dc may be performed by uncontrolled or controlled rectifiers. Modern uncontrolled rectifiers utilize silicon diode type rectifiers, which have replaced rotary converter and mercury arc type rectifiers. Controlled rectifiers are typically thyristor-controlled type rectifiers. Since both types of rectifiers perform the same basic function (conversion of ac to dc), both types will be referred to herein as "rectifiers" unless a distinction needs to be made between them.

b. DC traction power substation configurations vary from single transformer-rectifier units in small prefabricated buildings to multiple transformer-rectifier units in large, multi-story masonry buildings. In general, the larger facilities are associated with HRT systems, although this is not universally true. Selection of configuration is based on a number of factors that include capital cost, site availability, redundancy, and the design practices and standards of existing transit properties.

c. DC traction substations with two transformer-rectifier units are termed "double-ended" substations; ideally, both of these transformer-rectifier units are also powered from different ac supply circuits. This configuration is common for HRT systems, although additional rectifiers are often added to increase substation capacity.

d. The positive dc bus in a dc traction power substation having two or more rectifiers can be continuous, or it can be subdivided with bus tie breakers or disconnect switches. Subdivision of the positive bus provides a means to keep a portion of the dc switchgear in service if the positive bus is being maintained or repaired, or if dc switchgear is being replaced or extended. Bus subdivision with normally-open bus tie breakers may also be required in large, multi-rectifier substations to keep available short circuit currents within the ratings of the dc switchgear.

e. The negative dc bus in a dc traction power substation having two or more rectifiers is normally continuous. Commonly referred to as a "negative equalizer" bus, it provides a single location where negative return cables from the right-of-way can be terminated. The negative pole of each rectifier that is connected to the negative equalizer bus is provided with a disconnect switch (Device 89N) that is interlocked with the rectifier main dc circuit breaker. The purpose of this interlock is to preclude the operation of a rectifier with its negative polarity disconnected, which would be a hazardous condition.

f. DC traction substations in North America have traditionally used a rectifier main (cathode) dc circuit breaker for rectifier cathode switching and reverse current protection. This breaker was originally used to interrupt "arc-back" faults that could occur in mercury arc type rectifiers.

g. The substation configuration and enclosure should provide sufficient space to accommodate all traction power equipment and ancillary components with the necessary clearances during normal operation and maintenance. The equipment arrangement should provide adequate clearances and working space with equipment access doors opened, panels removed, and switchgear removable elements withdrawn.

Ceiling heights, aisles, floor hatches, hallways and structural openings should permit removal and replacement of the largest components installed in the substation.

h. Equipment arrangements, clearances and egress should comply with applicable local, state and national building, fire and electrical safety codes. Special attention should be paid to the clearances around the dc switchgear enclosures and rectifier enclosures, and to the electrical isolation typically required for these enclosures (refer to Section 12.3.9).

i. If substations are located below grade they should be constructed with adequately-sized and located equipment hatches to permit the removal of any item of equipment from the substation to the ground level above, or doors to permit the removal of equipment from the substation to track level.

j. DC traction power for use inside vehicle maintenance shop buildings is normally provided from dedicated shop substations equipped with a negative bus that is connected to the grounded shop tracks and shop building grounding system. This requires the contact system and running rails inside the maintenance shop buildings to be electrically isolated from the contact system and rails outside of the shop.

12.3.2 UTILITY AC SUPPLY CIRCUITS AND INTERFACE CONSIDERATIONS

a. For traction substations with a single ac supply circuit, it is recommended that adjacent substations be connected to different utility supply circuits, ideally from different utility distribution substations ("independent" supply circuits). For traction substations with two ac supply circuits, it is recommended that each ac supply circuit be independent.

b. Underground ac supply circuits are recommended wherever feasible for maximum reliability. Service entrance equipment connected to both underground and overhead ac supply circuits should include properly-sized station class surge arresters.

c. For new substations, it is common practice to contact the supplying electric utility early in the design process to determine their interconnection requirements and standard practices for equipment access and ownership, metering, switchgear, and relay protection.

d. For substations that employ controlled rectifiers, mitigation of potentially high levels of harmonics and low power factor in the ac supply circuits under certain load conditions may be required.

e. For traction substations receiving medium voltage power from a 4-wire electric utility service, connection of a utility supply circuit neutral to the traction substation ac ground bus should be investigated, if the connection is permitted by the utility. This connection provides the lowest impedance return path for traction substation ac ground fault current, improving ac ground fault protection and reducing the size of the traction substation grounding grid (see IEEE Standard 367, *IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and*

Induced Voltage from a Ground Fault for additional information). With this connection, there is a remote possibility of stray dc current flow through the neutral of a utility supply circuit that is connected to adjacent traction substations. Therefore, a utility neutral connection to the substation ac ground bus should be considered mainly for those substations that could most benefit from it due to factors such as a high utility available line-to-ground fault current, high site earth resistivity, small site, etc., unless engineering studies determine that potential stray currents can be successfully mitigated.

12.3.3 RECTIFIER TRANSFORMERS

a. Power rectifiers for traction power application require special transformers that can provide the number of secondary phases and the voltages and phase displacements required for rectification. In addition, these transformers must be designed to sustain the repeated overload cycles and intermittent contact system short circuits that are typical of electrified rail transit system operation. For this reason, a rectifier and its rectifier transformer must be designed as an integrated unit, which is typically referred to as a “transformer-rectifier unit”.

b. The manufacture and testing of rectifier transformers in North America is addressed by IEEE Std C57.18.10, *IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers*. This standard describes the available rectifier circuit configurations and overload cycles, and also provides application information. IEEE Standard C57.18.10 should be referenced for the design and specification of rectifier transformers.

c. The most common transformer-rectifier unit overload cycle specified in North American transit application is Extra Heavy Traction, which involves application of 100 percent rated load current continuously until constant temperatures have been reached by all parts of the rectifier unit, followed by 150 percent current for 2 hours and a superimposed cycle of overloads consisting of five periods of 1 minute each at 300 percent of rated load current, followed by one period of 450 percent of rated load amperes for 15 seconds at the end of the 2 hour period. These shorter periods are evenly spaced throughout the 2 hour period.

d. The Heavy Traction transformer-rectifier unit overload cycle is sometimes specified, typically for yard and shop use and some streetcar applications. It involves application of 100 percent rated load amperes continuously until constant temperatures have been reached by all parts of the rectifier unit, followed by either 150 percent current for 2 hours following 100 percent load, or 300 percent current for 1 minute following 100 percent load.

12.3.4 UNCONTROLLED POWER RECTIFIERS

a. Uncontrolled power rectifiers for traction applications are the traditional silicon diode type. These are available in a number of circuit configurations, the most common of which is the 12-pulse bridge type (“double way”). This type of rectifier requires a rectifier transformer with two secondary windings, one connected in delta, the other connected in wye, providing a 30° phase displacement between similar secondary phases. Each secondary winding is connected to a three-phase bridge rectifier circuit; the bridge circuits are typically connected in parallel through an interphase transformer in what is known as an IEEE Circuit 31 configuration, although other circuit configurations are sometimes employed.

b. The ac harmonic output of a rectifier decreases as the pulse number increases, which is a primary reason why 12-pulse rectification is typically preferred to 6-pulse rectification for all transit applications except small shop rectifiers and some historic streetcar systems. 12-pulse rectification may be obtained from one or more 12-pulse rectifiers. It may also be obtained in effect from matched pairs of separate 6-pulse bridge type transformer-rectifier units with 30° secondary phase displacement connected in parallel (one rectifier transformer secondary connected in wye, the other connected in delta). With the latter approach, when one of the two 6-pulse rectifiers is out of service, the remaining rectifier will provide 6-pulse rectification, resulting in an increase in the harmonics being injected into the ac supply circuit.

c. Current sharing between the two bridges of 12-pulse rectifiers can be sensitive to high levels of voltage distortion and phase unbalance in the primary ac supply; this is to some extent dependent on the rectifier and rectifier transformer design. In general, high levels of voltage distortion and phase unbalance in the rectifier primary ac supply should be avoided if possible. If this is not possible, then rectifier design studies based on actual measurements and consultations with rectifier manufacturers are recommended.

d. Uncontrolled power rectifiers are typically indoor type, utilizing convection cooling.

e. The manufacture and testing of uncontrolled power rectifiers was governed for many years by two standards, both of which have been long since rescinded: ANSI C34.2, *Practices and Requirements for Semiconductor Power Rectifiers*; and, NEMA RI 9, *Silicon Rectifier Units for Transportation Power Supplies*. These have been superseded by a the new IEEE Standard 1653.2, *Standard for Uncontrolled Traction Power Rectifiers for Substation Applications up to 1500 Volts DC Nominal Output*.

f. The various power rectifier circuit configurations that are commonly used in the transit industry are described in IEEE Standard 1653.2.

12.3.5 CONTROLLED POWER RECTIFIERS

a. Controlled power rectifiers employ thyristors to control the rectifier firing angle, thereby enabling control of the dc output voltage and current. These devices are typically manufactured in the 12-pulse bridge configuration. They are more commonly known in North America as thyristor-controlled rectifiers (TCR).

b. Controlled power rectifiers used in North America typically maintain a fixed (steady) output voltage up to 100-150% of rated full load current, after which the output voltage regulation becomes linear until it reaches maximum rated load current. TCRs will normally control (limit) their output to a maximum current after a short time delay that allows fault clearing by dc system protective devices.

c. Some TCR substations installed in North America have required the installation of capacitors on the primary side to improve power factor.

d. Controlled power rectifiers are typically indoor type, utilizing forced air cooling.

e. If permitted by the supplying utility, TCR substations can be designed to allow the flow of regenerated power from the dc traction system into the ac supply system, thus potentially improving the utilization of this power.

f. The manufacture and testing of controlled power rectifiers was governed for many years by ANSI C34.2, *Practices and Requirements for Semiconductor Power Rectifiers*, which has been rescinded. A new IEEE standard for controlled traction power rectifiers is being prepared by an IEEE Traction Power Substation Subcommittee Working Group.

12.3.6 DC POWER CIRCUIT BREAKERS

a. Rectifier main and dc feeder circuit breakers for modern transit application are draw-out type, single pole, high speed or semi-high speed. The high speed type are typically used for systems with high short circuit current availability, since they are designed to limit the current peak of the available (prospective) fault current by clearing any fault within 15 ms of inception.

b. The manufacture and testing of dc power circuit breakers in North America is currently addressed by IEEE standard C37.14, *Standard for Low-Voltage DC Power Circuit Breakers Used in Enclosures*. This standard also includes an application guide. Standard C37.14 currently refers to tables in IEEE Standard C37.16, *IEEE Standard for Preferred Ratings, Related Requirements and Application Recommendations for Low-Voltage AC (635 V and below) and DC (3200 V and below) Power Circuit Breakers,* for preferred electrical ratings and test values. The metal-enclosed switchgear assemblies in which the circuit breakers are housed are addressed by IEEE Standard C20.1, *Standard for Metal-Enclosed Low-Voltage Power Circuit Breaker Switchgear*.

c. A dc circuit breaker must be capable of interrupting the maximum available ("prospective") short-circuit current that could flow through the breaker, including contributions from nearby substations. IEEE Standard C37.16 provides two classifications for dc power circuit breaker short-circuit current interrupting ratings, light duty and heavy duty. The light duty classification corresponds to a 4000 kW source which is equivalent to a 100 kA short-circuit current interrupting rating for 800 Vdc class breakers. The heavy duty classification corresponds to a 8000 kW source which is equivalent to a 200 kA short-circuit current interrupting rating for 800 Vdc class breakers (See Annex A of IEEE Std. C37.14). These classifications are somewhat arbitrary and do not account for fault contributions from adjacent substations.

d. DC feeder breakers are equipped with integral instantaneous overcurrent “direct-acting” trip units (Device 176). The available setting range for the direct acting trip units is typically a multiple of the breaker frame size (the breaker continuous current rating), a constraint which must be considered in the selection of the appropriate frame size.

e. The direct-acting trip units for dc feeder breakers can be bidirectional or unidirectional. Unidirectional trip units that trip only for fault currents in the forward direction provide the most secure (selective) protection. Feeder breakers with bidirectional trip units could theoretically nuisance-trip on reverse current flow (infeed) when another breaker on the same bus is feeding a fault in the forward direction. This normally does not occur in practice because the breaker feeding the fault “sees” a high forward fault current that is the sum of the reverse currents in the other breakers plus the fault contribution from the substation rectifiers, and thus it trips first. This potential for miscoordination due to bidirectional trip units is greater for dc breakers in tie (gap) breaker stations, because tie breaker stations do not have the large fault current contributions from rectifiers that improve feeder breaker trip unit selectivity.

f. The most commonly used frame sizes for dc power circuit breakers conforming to IEEE standards are 4000, 6000 and 8000 Amperes, although other frame sizes are available.

g. The voltage classes for dc power circuit breakers conforming to IEEE standards are 800, 1000, 1200, 1600 and 3200 Vdc. The rated short circuit Amperes for heavy duty high-speed breakers for these voltage classes are 200 kA, 158 kA, 132 kA, 100 kA, and 50 kA, respectively. The 800 Vdc class is normally specified for transit systems with a 750 Vdc nominal voltage. The reason a higher voltage class is not normally needed is discussed in Section 10.2.1 of IEEE Standard C37.14-2002, which states: *Circuit breaker dielectric ratings have been selected to provide a margin for open-circuit voltage and voltages from regeneration. Normal operational voltages are less than maximum design levels and, during short circuit, the actual voltage is reduced to measurably less than operational.* Selection of a higher voltage class also results in a lower short circuit current rating.

12.3.7 RELAY PROTECTION FOR SUBSTATION DC EQUIPMENT

a. Transformer-rectifier units are typically protected on the ac side by overcurrent relays that trip the ac supply and dc cathode breakers upon detection of a fault or an overload. The current transformers employed for this protection are typically located on the load side bushings of the transformer-rectifier unit ac supply breaker. The phase overcurrent relaying must provide satisfactory overload protection while at the same time allowing the rectifier to sustain the short-time overloads that are defined by its service rating without nuisance tripping. For example, the relay protection for a rectifier with an IEEE Extra Heavy Traction service rating must be able to sustain a 450% overload for 15 seconds without nuisance tripping, while also providing protection against thermally damaging overloads. To properly select and set the unit overcurrent relays, time-current curves should be prepared that show the rectifier service rating overload characteristic and available short circuit current as well as the proposed relay curves.

b. Rectifiers are typically protected on the dc side by direct-acting instantaneous reverse overcurrent trip units (Device 32 or 132) that are built into the rectifier cathode breakers.

c. Miscellaneous protections for power rectifiers include the following, although practices and device numbers vary widely among transit agencies. In addition, the device numbers have not been formally standardized.

Table 1 - Typical Rectifier Protective Device Numbers

Number	Protective Device Description
26R1	Rectifier diode overtemperature—first stage
26R2	Rectifier diode overtemperature—second stage
33X	Rectifier enclosure door open
57G	Grounding device
63A	Rectifier low air flow (forced-cooled only)
64	Rectifier enclosure energized—trip
64G	Rectifier enclosure grounded—alarm
98A	Rectifier diode failure—first stage
98T	Rectifier diode failure—second stage
99A	Rectifier surge protection failure

d. Modern relay protection for substation feeder circuit breakers normally includes instantaneous overcurrent, short-time overcurrent, long-time overcurrent, and current rate-of-rise detection. The purpose of the rate-of-rise detection is to discriminate between fault currents and the load currents of accelerating trains, since the load currents can be higher than the currents resulting from remote faults. The rate-of-rise function should include ΔI (change in current) and Δt (time delay) settings; these can be adjusted to provide better protection against nuisance trips caused by rolling stock electrical characteristics. The dc current input reference for the relays is obtained from shunts mounted in each circuit breaker termination compartment; the shunts are typically sized to provide a 50 mV signal when conducting circuit breaker full load current.

e. Some light rail systems power the inbound and outbound tracks in double track mainline areas from a single (shared) feeder breaker (each substation has just two dc feeder breakers). While economical to construct, this approach can negatively impact operations as well as limit the effectiveness of the OCS relay protection. With this arrangement, a fault on either track will cause the OCS for both tracks to be de-energized until the fault can be located. In addition, unless separate feeder cables and current measuring shunts are provided for each track, the feeder breaker relays cannot determine which track's OCS is overloaded, rendering OCS thermal and long-time protection ineffective. Light rail systems that support frequent service should be equipped with four mainline dc feeder breakers per substation so that inbound and outbound tracks are powered from separate circuit breakers, and are electrically independent. With the four-breaker arrangement, a fault on one track will de-energize the OCS for the faulted track only.

f. Some traction power systems employ transfer tripping as part of the protective scheme for feeder breakers that power the same OCS or contact rail section. Transfer trip (IEEE Device 85) causes all circuit breakers powering a contact section to trip if any one of them trips. This provides improved electrical protection for remote faults, but the resulting operational impact of complete power removal to a section due to nuisance trips should also be considered. The negative operational impacts can be mitigated if the circuit breaker that originates the trip signal is permitted, under the appropriate conditions, to perform the normal auto-reclosing cycle before sending the transfer trip signal. The communications used for transfer tripping should be dedicated, point-to-point type circuits or channels.

g. DC feeder circuit breakers powering OCS or contact rail sections are normally equipped with automatic reclosing capability. Control of the automatic reclosing is normally provided by combined voltage measuring (Device 83 or 183) and load measuring (Device 82 or 182) schemes that attempt to determine if an automatic breaker tripping is the result of a permanent fault, a temporary (transient) fault, an overload, or a nuisance trip. After a feeder breaker is tripped by automatic means, the scheme measures the voltage on the load side of the open feeder breaker; this measurement is performed after an adjustable time delay of several seconds. Modern relays also provide adjustable settings for the duration of the voltage measurement interval; longer measurement intervals are sometimes required to allow the inrush currents typical of modern rolling stock propulsion and auxiliary power systems to dissipate. Depending on the measured voltage, three conditions could occur.

1) If the measured voltage is above a set threshold (V_{max}), the section is assumed to be fault-free, and the breaker will immediately reclose.

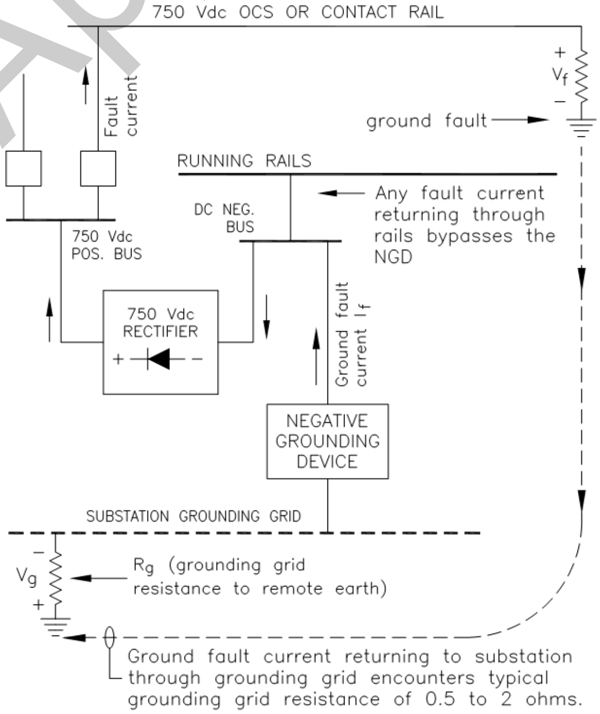
2) If the measured voltage is below a minimum threshold (V_{min}), the breaker will begin what is called a "load measuring cycle"; a fixed resistance will be inserted in parallel with the open feeder breaker contacts, and the resulting voltage and current will be measured. The resulting calculated load resistance (the measured voltage divided by the measured current) will then be compared against a minimum load resistance threshold Ω_{min}. If the measured resistance is below Ω_{min}, then a permanent fault is assumed to exist, and the breaker will be locked out. If the measured resistance is above Ω_{min}, the breaker can be reclosed. Most load measuring schemes allow the load measuring cycle to be repeated one or two additional times for more positive confirmation of a fault-free condition, if desired.

3) If the measured voltage is between V_{max} and V_{min}, the breaker will not be allowed to close, since a high resistance fault may be present. If additional load measuring cycles do not detect voltages outside of these limits, the breaker will

be locked out. This indefinite condition, which is referred to by traction power relay engineers as “no man’s land”, should be avoided to the extent possible by appropriate relay setting, particularly for single-ended power sections (contact sections powered by a single feeder breaker).

h. The consistent detection and clearing of dc short circuits that involve a ground return path (ground faults) has traditionally been a challenge with dc traction. Ground faults caused by feeder cable insulation breakdown, contact rail insulator failure, track debris, broken OCS equipment, salt-laden snow, and other unforeseen events can result in low levels of short circuit current flow insufficient to operate the substation feeder breaker overcurrent relays. These ground faults may manage to evade rate-of-rise and long-time overcurrent relay settings and still produce hazardous touch voltages and sufficient energy to damage equipment. This has been an industry-wide dilemma for many years; if the relays are set to be highly sensitive, then nuisance tripping is frequent and operations are negatively impacted.

i. Alternative methods of either permanently or temporarily connecting the substation dc negative bus to ground have been tried as an aid to ground fault detection. This topic is too complex to describe in this section, but considerable industry literature is available describing these methods and their results. In summary, the approach that has been gaining the greatest acceptance is the use of a normally ungrounded dc negative bus in combination with a device that temporarily connects the negative bus to the substation grounding grid if the voltage between them becomes excessive (high voltage between the negative bus and grounding grid is an indication of a ground fault). The closure of this device is intended to allow the normal feeder breaker relays to detect the fault and clear just the faulted section. These devices are known by such names as automatic grounding switch, short circuiting device, and negative grounding device (“NGD”, which will be used here for convenience). Standards for NGDs and their application such as IEC 62128-1 [2] have existed for many years in Europe. NGDs built to comply with IEC 62128-1 are termed Voltage-Limiting Devices. IEC 62128-1 includes a voltage versus time curve that specifies the maximum permissible durations for touch voltages; NGD equipment built to this standard must clamp the highest voltages in no more than 20 milliseconds. Voltage limiting devices typically include power electronic switching devices such as thyristors in order to achieve the required clamping speeds.



Any fault current returning through rails bypasses the NGD

Ground fault current returning to substation through grounding grid encounters typical grounding grid resistance of 0.5 to 2 ohms.

j. A very simplified circuit diagram illustrating a typical NGD arrangement for a 750 Vdc nominal system is shown in the accompanying figure. The NGD is normally in an open state (non-conducting), measuring the voltage between the negative bus and grounding grid. As long as the NGD remains open, significant fault current cannot flow back to the substation dc negative bus. A small amount of fault current will flow into the rails near the fault via the distributed leakage/shunt resistance of the rails, in proportion to how well they are insulated from earth. After the NGD senses a triggering voltage difference across it and closes, the fault current will flow through the earth into the substation grounding grid. The fault current will be limited by the resistance of the grounding grid to remote earth, Rg. For example, if the grid resistance is 1 Ohm, and the other typically smaller circuit resistances are neglected, the ground fault current will be 750 V/1 Ω, or 750 Amperes dc. This is a relative low value of current for purposes of protective relaying. It is clear from this example that the substation grounding grid resistance Rg must be made as low as practicable for the NGD to work effectively.

12.3.8 SURGE PROTECTION FOR SUBSTATION DC EQUIPMENT

a. Rectifiers and dc switchgear assemblies conforming to IEEE standards have substantial dielectric ratings for primary circuits. For example, the primary circuits of the most common 800 Vdc voltage class of circuit breakers and rectifiers are built to withstand a 60 second rms design test voltage of 3700 Vac or the equivalent 5200 Vdc. The secondary control wiring is built to sustain a 60 second rms design test voltage of 1500 Vac (2100 Vdc). Field dielectric tests are limited to 75% of these values per IEEE standards. Surge protection for this equipment should limit worst case surge voltages to levels below the field dielectric test values.

b. Since the sources of most potentially damaging electrical surges for traction power substation dc equipment are external to the substation, surge protection is typically provided on the line (contact system) side of dc feeder breakers, and also at the riser structures for OCS (aerial) feeders on the line side of riser disconnect switches. MOV type surge arresters in polymer housings designed for dc system application are used at these locations. The circuit breaker line side arresters should be installed at secure locations outside of the circuit breaker enclosures so that potential arrester operation or rupture will not damage the dc switchgear. This also precludes the need to bring a ground connection into the dc switchgear, a practice which should be avoided.

c. Surge protection for indoor rectifier transformers is typically provided by surge arresters that are located in the incoming medium voltage switchgear.

d. In general, dc surge arresters that have a maximum continuous overvoltage (MCOV) rating that is slightly above the maximum substation no-load dc voltage (including regeneration, if applicable) will provide the best equipment protection. An insulation coordination study is recommended for selection of the appropriate arresters.

e. Satisfactory equipment protection from surge arresters requires that they be connected directly to a low-resistance ground reference; for the dc feeder breaker line side arresters and the incoming ac service arresters, the lowest resistance reference is the substation grounding grid. To provide the most effective surge protection, the substation grounding grid should be designed to have as low a resistance to remote earth as practicable. Some substation designers have provided separate ground grids for ac and dc equipment and surge arrester grounding under the theory that the worst case ground potential rise (GPR) resulting from bolted ground faults on the ac supply equipment could damage dc equipment. However, if the grounding grid is appropriately designed in accordance with IEEE Standard 80 to minimize GPR, a single large, low resistance grid will be adequate; this is the traditional approach to traction power substation grounding grid design, and it is recommended. As noted above, the dc traction power equipment has generous dielectric ratings.

12.3.9 GROUNDING OF SUBSTATION DC EQUIPMENT ENCLOSURES

a. Two approaches are commonly used in North America for the grounding of dc traction power equipment enclosures. Both approaches isolate the rectifier and dc switchgear enclosures from ground. Electrical isolation is provided by installing insulated flooring under the enclosures and around them to a perimeter extending five to six feet from the enclosures on sides that do not have working access doors. On sides containing working access doors such as circuit breaker and control compartment doors, the insulated flooring should extend far enough to include work being performed with access doors open. If space constraints require grounded equipment, walls or metallic items to be inside this insulated zone perimeter, they must be covered with suitable electrical insulation such as flame-retardant fiberglass-reinforced polyester laminate sheeting manufactured in accordance with NEMA GPO standards.

b. With both equipment enclosure grounding approaches, supervised relays are provided between the rectifier and dc switchgear enclosures and ground to monitor the status of the electrical isolation between the enclosures and ground. If a grounded condition is detected by the relay (Device 64G), an alarm is normally provided. If an energized ("hot structure") condition is detected by the relay (Device 64), all connected equipment is tripped and locked-out. The approach most common in the USA is to use a high resistance relay that limits the current during a positive-to-enclosure fault to several Amperes while allowing the voltage on the insulated enclosure to approach system nominal voltage. The alternate approach employs a low resistance relay that limits the voltage on the enclosure to no more than five Volts, but permits a significant fault current flow.

c. DC feeder breaker relaying for substations employing low resistance enclosure grounding should include transfer tripping and adequate relay protection against reverse direction faults to ensure that all possible infeeds to an insulated dc enclosure fault will be cleared.

d. Special anchors must be used for dc switchgear and rectifier enclosures to prevent bridging of the insulated flooring. Electrical isolation must also be provided at bus duct enclosure connections to rectifiers and dc switchgear. Electrical isolation must also be provided for metallic raceway connections to these enclosures such as conduits and cable tray, although fiberglass cable tray and fiberglass (NEC type RNMC) conduit is typically used in the insulated zone to maintain electrical isolation.

SECTION 12.4 - DC TRACTION POWER DISTRIBUTION SYSTEM

12.4.1 POSITIVE SUPPLY AND NEGATIVE RETURN CIRCUITS - GENERAL

a. The positive supply portion of a traction power dc distribution system consists of the distribution equipment between the dc feeder circuit breakers and the connections to the OCS or contact rail system. This normally consists of electrical conductors and disconnect switches, which are covered elsewhere in this chapter, and cable raceway systems. Traction power cable raceway systems include duct banks, distribution manholes and handholes, conduits, cable trays, and cable supports.

b. The negative return portion of a traction power dc distribution system consists of the distribution equipment between the connections to the running rails and the substation dc negative bus. Connections to the running rails typically involve impedance bonds in signaled portions of track, although some heavy commuter rail properties employ tuned reactors instead of impedance bonds for broken rail protection that accommodate negative return circuit currents exceeding the electrical ratings of standard impedance bonds. The same distribution equipment used for the positive supply equipment is also used for the negative return portion, with the exception of disconnect switches (negative return distribution circuits are normally never switched).

c. DC positive and negative return distribution circuits are normally segregated from each other to the maximum extent possible to minimize the possibility of potentially damaging dc short circuits occurring between them. Separate raceways, manholes and handholes are normally provided.

d. Raceways for positive and negative return circuits are normally non-metallic to preclude the possibility of their becoming energized by cable insulation failure. Since dc traction power systems are normally operated ungrounded, an energized raceway ground fault could be difficult for substation feeder breaker relays to detect. Non-metallic conduit types in common usage are PVC and FRE (NEC type RTRC). FRE has a significantly lower coefficient of friction for cable pulling than PVC, a lower coefficient of expansion, and can be obtained in low smoke, zero halogen formulations and formulations that meet NFPA 130 flammability requirements for surface mounted conduits. PVC-coated galvanized rigid steel conduit can be used for feeder risers where mandated for mechanical protection, and it can be field-bent to navigate obstructions. However, care must be taken during installation to protect the integrity of the internal PVC coating. Heavy wall FRE conduit is preferred for feeder riser application.

e. DC positive and negative return circuits installed in cable tray should be designed in accordance with the NEC. To obtain maximum circuit ampacity, cable trays should be the ladder or ventilated type, and the cables therein installed with at least one cable diameter of spacing between them (side-by-side installation reduces cable ampacity by 25% per NEC Article 392). Fiberglass cable tray is preferred for positive and negative return circuits to preclude the possibility of the tray becoming energized by cable insulation failure.

f. DC positive and negative cable routing inside substations can also be accomplished by the use of cable support racks comprised of structural channel assemblies. Cables are fixed in position on the racks with porcelain or epoxy insulated cable clamps. This arrangement allows maximum cable ampacity (no derating of cables due to close proximity is required).

12.4.2 POSITIVE SUPPLY SYSTEM SECTIONALIZING

a. Sectionalizing for dc traction power systems is the dividing up of the positive supply system into electrical segments to better facilitate electrical protection, operational flexibility, and electrical safety.

b. Section breaks in contact rail systems are provided by gaps in the contact rail.

c. Section breaks in dc overhead contact systems are provided by section insulators or by insulated overlaps (see Sections 4.2.9 and 4.3).

d. Section breaks in dc traction power systems that utilize contact rail have traditionally been the non-bridging type, meaning that two adjacent sections cannot be connected (bridged) by a single rail vehicle or group of electrically-connected vehicles (a “married pair”, for example). Some newer systems have used bridgeable contact rail gaps to accommodate rolling stock that requires a continuous power supply, but this practice is unusual in North America.

e. Section breaks are typically provided near substations to minimize the lengths of positive supply and negative return circuits to the ROW. Normally open disconnect switches are typically installed across the section breaks at these locations to permit the adjacent sections to be connected together when the substation dc switchgear or dc feeders are out of service.

f. Section breaks are provided on crossover tracks to electrically isolate adjacent tracks under normal operations. Normally-closed section breaks are also provided on the through tracks just before and after crossovers to permit segments of OCS or contact rail to be removed from service while keeping the crossover operational. The OCS typically employs normally-closed disconnect switches to provide sectionalizing at crossovers, while contact rail systems employ indoor circuit breakers and additional feeders.

g. Some contact systems use tie (gap) breaker stations to provide the additional feeders required to sectionalize remote crossovers, and to provide emergency sectionalizing between adjacent substations. Tie breaker stations used for this purpose connect the contact systems of inbound and outbound tracks together near the midpoint location between two substations. Interconnecting the contact systems of adjacent tracks near the section midpoint increases voltage at the trains and maximizes the opportunity for absorption of power from train regenerative braking. It can also improve fault detection by increasing the available fault current at remote (mid-section) faults, and by dividing a power section between two substations into two smaller sub-sections, each with their own protective relaying.

h. Section breaks are typically provided between main lines and storage yards to provide electrical isolation between them under normal operations.

12.4.3 CONTACT RAIL

a. Contact rail in North America has two configurations, over-running and under-running. In the overrunning configuration, the vehicle current collector paddles (shoes) ride on the upper surface of the contact rail. In the under-running configuration, the collector shoes ride on the bottom surface. In North America at present, use of the under-running configuration is limited to Metro-North Railroad and SEPTA.

b. With the over-running configuration, the contact rail is supported from beneath by porcelain or fiberglass post type insulators. With the under-running configuration, the contact rail is supported beneath insulated brackets that attach to the top of the contact rail. The support insulators are bolted to extended ties or tie extender plate assemblies at approximately every 5th or 6th tie. With both configurations, the contact rail is allowed to slide along the surface of the supports to allow for expansion and contraction.

c. The under-running configuration does not require a coverboard, since the upper three sides of the contact rail can be covered with electrical insulation. It also does not require heating strips to keep the contact surface free of ice. The over-running configuration requires both of these accessories.

d. Two types of contact rail are in widespread use, steel and composite. The most commonly-used steel contact rail is the 150 lb NMC section. Type 150 lb NMC has a nominal electrical resistance of 0.00360 Ohms/1000 ft. at 20°C, and a nominal weight of 150 lbs/yard.

e. Composite type contact rail is comprised of a steel rail section with aluminum conductor bars huck-bolted to each side of the rail web. The current collector shoe rides on the head of the steel rail section. The most common steel rail sections used for composite rail are the 84C, which is a replacement for 150 lb NMC steel rail, and the 85 lb section. Both sections have a nominal electrical resistance of 0.002 Ohms/1000 ft. at 20°C, and a nominal weight of 105 lbs/yard.

f. Aluminum contact rail, which is widely used overseas, has an aluminum body attached to a stainless steel wear strip. The resistance for this type of rail can be significantly lower than that of composite contact rail, with nominal values of .0014 Ohms/1000 feet at 20°C available in the USA, corresponding to a nominal weight of 52.5 lbs/yard.

g. Contact rail is typically manufactured and delivered in 39 foot sections (“sticks”). To minimize waste during construction, the lengths of contact rail segments in contact rail layout designs should be multiples of the standard section length, to the extent feasible.

h. Contact rail design practices and standards vary considerably between transit properties. However, the following general guidelines can be considered typical.

   1) The length of contact rail gaps in areas of complex trackwork must be coordinated with the types and consists of electrified rolling stock that will traverse them. In general, gaps that are intended to be “bridged” must provide continuous power to the shortest consist and/or the vehicle with the shortest distance between collector shoes. An analysis should also be performed to confirm that vehicles will not lose power and stop in non-bridgeable gaps, while also ensuring that the gaps will not be bridged

   2) Inclined rail sections (end approaches) are used at gaps in the contact rail to guide and transition the current-collecting shoes to the contact surface elevation, minimizing collector shoe bounce and the resulting arcing. These typically vary in length from 6 to 12 feet. The choice of length is a function of vehicle speed, available space, and agency standards. Longer lengths provide the least collector shoe bounce at high speeds.

   3) BART uses “dip rail” sections instead of gaps at some locations. Dip rail sections allow the contact rail to remain continuous, but at a low elevation that avoids contact with the collector shoes.

   4) Inclined side approaches are used by a few properties to transition the shoes to the contact rail at turnouts. This practice avoids the need for a gap in the contact rail for the tangent (through) track. If side approaches are not used, the tip of the end approach on the toe side of the switch must be offset from the toe of the switch by a clearance that varies by agency, but 7.5 feet is typical.

   5) Protective coverboards for over-running systems should extend between 12-18 inches beyond the tip of the end approach.

   6) Contact rail through passenger stations should be located at trackside opposite the station platform.

   7) Contact rail at grade should be located in the area between running tracks, except at yard areas, special trackwork, and through center platform stations.

   8) In sections of contact rail of 2,000 ft or less, a contact rail anchor should be provided at midpoint; otherwise, rail anchors should be provided at maximum 1,000 ft intervals at midpoint between expansion joints. Spacing of anchors should be adjusted to provide an anchor near the middle of curved sections, with expansion joints at points of tangent.

   9) Contact rail joints should be free of misalignment or roughness. Bolted butt joints should have minimum gap between rail ends and be ground smooth to minimize wear and abrasion on collector shoes.

10) Continuity jumper cables between contact rail gaps and expansion joints should be of equal length to equalize the currents flowing through them.

11) Clearances between the contact rail and coverboards, running rails, collector shoes and surrounding infrastructure vary with contact rail and running rail type and transit agency standards. Contact rail system design must be based on the clearance diagrams for the transit agency for whom the design is being performed.

12.4.4 DC TRACTION POWER CABLES

a. DC traction power cables should be stranded, copper conductors with insulation rated for at least 2,000 Vdc or a voltage consistent with system design voltage. Non-shielded construction is typical, however, some transit agencies use shielded construction for positive feeder cables as part of an insulation failure detection scheme.

b. The copper used for the conductor should be soft-drawn type conforming to ASTM B8 with Class C or D stranding. Cable insulation should be EPR, protected by a polyvinyl chloride (PVC) jacket for above-ground applications, or a flame-retardant, low-smoke, non-halogen, cross-linked polyolefin (XLPO) jacket where required.

c. Cable insulation temperature rating should match the maximum temperature of the terminations used but should not exceed 90 °C conductor temperature for normal operation in wet or dry locations, 130 °C for emergency operation, and 250 °C for short-circuit conditions.

d. Traction power cables connecting dc feeder breakers to the overhead contact system (OCS) or third rail, and from running rails to the negative bus, should be sized to sustain maximum overload and short-circuit currents with a temperature rise not to exceed the insulation design limits of the cables based on a minimum insulation life of 40 years.

e. Feeder cables should be of a common conductor size, using multiple conductors as required to accommodate the ampacity requirements for different circuits.

f. Conductor size should be selected so as to minimize life cycle costs which include costs of installation, raceway construction, and electrical losses.

g. Maximum cable ampacity should not be compromised by the use of different types of raceway arrangements for various sections of the feeder.

h. Feeder cables should have sufficient conductivity to maintain traction power voltage levels within the specified limits, confining the significant voltage drops to the contact system and the running rails.

i. The traction power feeder cables must be sized so that they do not exceed rated cable insulation temperature during expected operating conditions. The current-carrying capacity requirements for sizing the positive and negative cables should be determined by load flow studies.

j. As a rule of thumb, the current carrying capacity of the negative cables at a substation should be approximately equal to the current carrying capacity of the substation positive cables. However, it is recommended that the results of load flow studies be used to determine the precise number of cables required.

k. Since contact rails and OCS conductors will vibrate due to operations and move due to temperature, their cable terminations should be designed to assure sufficient flexibility to preclude cable failure. OCS feeder cables should terminate at a junction box at the base of the OCS support pole or on a riser pole disconnect switch, if present, with extra-flexible stranded "jumper" cables utilized for the final connection to the OCS conductors. Contact rail feeder cables should terminate at a pothead near the contact rail, and extra-flexible jumper cables utilized for the final connection to the contact rail.

l. Surge protection should be provided for underground positive feeders at raceway system entry and exit locations.

m. Raceways containing dc traction power cables should be nonmetallic to preclude the possibility of the raceway becoming energized due to cable insulation failure. Since dc traction power systems are normally operated ungrounded, the grounding of metallic raceways containing dc cables may be ineffective.

n. Cable supports in manholes and handholes should be non-metallic.

o. Underground raceway system design parameters such as conduit size, cable tensions, maximum total angle of bends, minimum embedment depth below grade, manhole spacing and duct gradient should be in accordance with NEC, NESC and cable manufacturer requirements. Feeder ductwork should be identified by a red warning tape 6 inches wide marked "Caution – Buried High Voltage Cable Below," installed 12 inches above concrete encasement in backfill. It is recommended that the concrete encasement include a red dye additive.

p. Feeder ductwork should be run as directly as practicable and should be located to avoid interference with foundations, utilities, and similar underground facilities.

12.4.5 DC DISCONNECT SWITCHES

a. DC disconnect switches are devices that will open the circuit of a direct current power system; they are classified as load break or non-load break, and manual or motorized. A load break switch is designed to interrupt its rated current when opened, while a non-load break switch cannot be opened under any load and the line must be de-energized when the switch is opened.

b. Motorized switches are operated through a mechanism by a motor that can be locally or remotely controlled. They usually have an override feature that allows them to be operated manually. Manual disconnect switches are operated by hand or hookstick so that the person performing the switching operation physically pulls the switch blade open or pushes it closed. Manually operated switches should not be opened under load unless they are specifically designed to do so.

c. Switch current-carrying components should be made from copper or copper alloys and may be silver plated. Copper and copper alloys should conform to ASTM B187 and silver plating should range from 0.20 mils to 3.0 mils thick with the contact area having the greatest thickness. Silver plating should conform to ASTM B700.

d. In locations having extreme industrial pollution such as nearby refineries and paper mills where high hydrogen sulphide gas exists in the air, tin plating should be substituted for silver plating. Tin thickness should be in the range 0f 0.001-0.003 inches conforming to ASTM B545.

e. Switch insulating components such as mounting bases should be made from composite insulating materials conforming to NEMA Grade GPO-3 (minimum) when mounted in enclosures with an insulating base. They may also be mounted on insulators of polyester based resins or of high grade wet process porcelain. Bolts used for mounting the base, insulators or other switch components must be completely covered or insulated if exposed on the outside surface of the enclosure.

f. Switches can be placed in enclosures or mounted on insulators and supports without an enclosure so that all parts are exposed. For maximum safety and maintenance considerations, disconnect switches should be placed in non-conducting enclosures in such a manner that no part of the enclosure will contact the energized portions of the switch and any physical contact by personnel to the outside of the enclosure will not result in electric shock. All enclosure metallic components must be completely insulated and incapable of becoming energized. Enclosures should have ventilation to prevent moisture buildup; this can be accomplished with louver type vents, either metallic or plastic, but metallic vents should be completely insulated on the inside of the enclosure.

g. Switch design should conform in all aspects to IEEE Std C37.30, *IEEE Standard Requirements for High-Voltage Switches*, for temperature rise. Many styles of disconnect switches are available from manufacturers but no matter what type is chosen, it should conform to these recommendations. Styles of switches can be, but are not limited to, knife blade, arcing horn or plunger. The more practical and economical type of switch is the knife blade type where the blade pivots 180° around a hinge and inserts into a jaw. This type usually provides maximum electrical clearance between the jaw and hinge when in the open position.

h. The electrical contact surfaces of the switch should have sufficient, consistent pressure that when closed, the insertion of a feeler gage with a thickness of 0.002 inches (0.05 mm) or greater cannot be inserted between the two contact surfaces for non pressure bolted switches. Pressure bolted switches have the jaw contacts forcibly closed for maximum pressure and hence, low resistance.

i. Switches should be designed for the intended load as well as emergency overloads and the designer must consider this to prevent switches from overheating when in operation. Switch dielectric ratings must accommodate the voltage being applied including voltage rise due to transients and vehicle regeneration. The BIL of the enclosure and ancillary insulation, or insulators if not in an enclosure, shall match or exceed the BIL of the cable to which they are attached.

j. Mounting of switches in enclosures should be such that environmental surroundings do not compromise switch operation. On rights of way, switches should be mounted vertically on stanchions away from tracks where possible so that personnel can operate them with adequate clearance from rolling stock. On public streets, they should be placed on OCS support poles at a height above the sidewalk where the public cannot access them. Minimum height should be at a level consistent with the operating agency's standards or local and national safety codes such as the NESC. This is typically a minimum of 8 feet when mounted in public thoroughfares.

k. For disconnect switches mounted on poles or structures where personnel access is not possible, insulated operating rods with handles should be employed. These must have sufficient insulation for the operating voltage to prevent electric shock and should be mounted so that they are inaccessible to the public. Operating rods must be of sufficient strength to prevent bending when operating the switch and should be able to be fully operated in all types of weather conditions, including ice buildup, without damage.

l. Switch devices that use manually operated handles that are located within the enclosure must be of a non-conducting material and so constructed that repeated operations do not cause material failure. They must be designed so that when the enclosure door is opened, a restraint will not permit the handles to fall out. For side operated switches, metallic handles must be completely insulated from the interior of the switch mechanism so that voltage cannot accidently be impressed onto the handle. Non-conducting or insulated metallic handles should be considered by the purchaser of the equipment for additional protection from electric shock.

m. Switches installed in subways or tunnels should be located where sufficient clearance to trains can be maintained on tangent and curved track and should be mounted on tunnel walls or other structures in the vertical position. When clearances are extremely tight and switch enclosures must be placed between tracks and/or third rails, the enclosure door should open parallel to the track so if left in the open position, it will not be struck by any portion of the train.

n. Switch operating mechanisms or enclosures should be equipped with an agency approved lock to prevent unauthorized access. This may require simple padlocks or Kirk Key type interlocks. Enclosures or open faced switches should have identification signs or name plates conforming to the operating agency's standards. When two or more switches are ganged in an enclosure or mounting, the group can be identified as one switch location, primary number with sub numbers or each individual switch with a separate number. Enclosure identification signs should be easily readable with permanent letters and numbers. Switch position should either be indicated or visible to the operator.

o. Motor operated switches must have local provisions to render the switch inoperable. The device must be highly visible and the position of the automatic and local features easily accessible but immune from accidental operation.

p. Cables attached to vertically mounted switches should be supported so that undue strain is not placed on the switch components and to prevent the cables from moving when they are disconnected from the switch termination bus bar. Cables should have identification tags placed on them in the enclosure identifying the cable number or circuit number. Where there is extreme moisture buildup in the enclosure and it “wicks” into the strands of the attached cables, the cable ends should be soldered solid and a moisture resistant insulating compound or heat shrink tubing should be used to cover the strand-to-insulation interface, preventing moisture ingress into the cable.

q. Disconnect switches mounted on OCS poles or on rights of way where cables exit from underground conduit should be provided with polymer housed, MOV type surge arresters. The arresters should be connected on the contact system (load) side of the switch, outside of the switch enclosure, and be provided with a direct connection to a ground rod or ground road array. No arrester connections should be made inside of the switch enclosure.

SECTION 12.5 - DC TRACTION POWER SYSTEM PLANNING AND DESIGN

12.5.1 LOAD FLOW SIMULATION STUDIES

a. Load flow simulation studies for existing or new dc traction power systems are used to predict the performance of the system design under a variety of conditions. The results of the studies provide a basis for the location and sizing of the traction power equipment.

b. Load flow simulation studies for dc traction power systems are in general more complicated and demanding than load flow studies for commercial electric power systems, requiring the use of specialized software and numerical techniques. DC systems have a negative return electrical network that must be incorporated into the network solution, unlike the neutral return in a balanced three-phase ac network that can be omitted. There is also no system "steady state" for a dc traction power system, that is, the major loads on the power system are physically moving as well as significantly changing in magnitude with time. Contact system temperatures increase and decrease as trains approach and pass. For systems employing transit vehicle regenerative braking, the analytical challenge is compounded by the constraint of one-way power flow through the substation rectifiers typically in use today. Moreover, the amount of regenerated power actually utilized at a given instant is dependent on the position and magnitude of other loads and regenerating vehicles at that instant. Power is exchanged between neighboring substations as dc bus voltages vary under changing loads. This presents a dynamic load flow problem that requires analytically advanced software and understanding on the part of those performing the studies.

c. The impedance of wires, cables and rails in a direct current power system has only a resistive component that is proportional to operating temperature. To obtain accurate, “real-world” results in load flow studies, it is important to use realistic operating temperatures when selecting equivalent resistances for these components. This is true for OCS, contact rail and running rail in particular, since the greatest proportion of voltage drop typically occurs across these elements. Contact and running rails have large cross-sectional areas, and tend to cool quickly. Continuous-welded rail is also designed to operate within a limited temperature range. To verify assumptions, field measurements of OCS and rail temperatures can be easily made from a distance using infrared thermometers.

d. The IEEE Traction Power Substation Subcommittee is currently in the final stages of developing IEEE P1653-3, *Trial-Use Guide for Traction Power Systems Modeling*. This document provides a much better description of this complex topic than can be satisfactory described in this section, and reference to it is recommended.

e. Modern load flow simulation software is capable of providing the following information as an aid to system analysis and design.
    1) Load currents throughout the dc positive and negative return electrical networks;
    2) Voltages at trains between the positive current collectors and the return rails, and any other location on the traction power system;
    3) Running rail-to-earth voltages, and stray current flows through earth and metallic structures;
    4) OCS conductor operating temperatures;
    5) System energy losses in individual system components as total system losses;
    6) Substation metered demand and energy consumption;
    7) Power and energy regenerated into the electrical system during braking; and
    8) System receptivity to regenerated power.

12.5.2 SUBSTATION LOCATION

12.5.2.1 Basis for Substation Location and Rating

The selection of suitable locations for traction power substations (TPSS) should include an evaluation of the following considerations as a minimum.

a. Load flow study findings for normal operation and contingency operation conditions.

b. Minimizing the distance between the substations and the right-of-way (ROW), to minimize the lengths of positive feeder and negative return circuits between the ROW and TPSS.

c. Potential above-ground and below-ground utility conflicts between the TPSS and the associated feeder and negative return circuit terminations on the ROW.

d. Availability and cost of medium voltage service from the applicable electric utility.

e. Visual impact on surroundings/neighborhood.

f. Subsurface conditions: the presence of shallow ledge is normally cost-prohibitive for duct bank and substation foundation installation, and it complicates substation grounding.

g. Construction access: suitability for equipment transport and rigging for the initial installation and for equipment replacement.

h. Maintenance access: the avoidance of access roads that require a track crossing as the sole means of vehicular access is recommended.

12.5.2.2 Normal Operation

Normal operation describes the functioning of a traction power system when all traction power equipment is in service and operating at full electrical ratings. The location and rating of TPSS should provide a minimum vehicle operating voltage that allows full performance during normal operation. This requirement typically pertains to peak service periods and to the ultimate design headway, train consist, and vehicle parameters for the traction power system. Full performance refers to full (normal) acceleration (see Section 3.2.4).

During normal operation, all traction power equipment thermal ratings should be below maximum rated values for the duration of the peak service periods.

12.5.2.3 Contingency Operation

Contingency operation describes the functioning of a traction power system with one or more items of traction power equipment out of service, typically for at least the peak service period. “Single contingency” refers to operation with any single item of equipment out of service. “Double contingency” refers to any two items of equipment out of service.

Requirements for contingency operation vary among transit agencies, and between LRT and HRT systems. Requirements for contingency operation on existing transit systems are usually defined in the traction power design criteria for those systems. However, the following guidelines can be considered typical for use on new systems, or systems that do not have established design criteria.

a. The location and rating of TPSS should provide a minimum rail vehicle voltage that supports peak period service during single contingency operation, but not at full performance. The contingency minimum vehicle operating voltage (See Section 3.2.5) is dependent on system voltage and rolling stock. Rolling stock equipped with forced reduced performance capability can typically sustain a higher contingency minimum vehicle operating voltage.

b. For systems that utilize substations containing more than one transformer-rectifier unit, the rail vehicles must operate at full performance with any single transformer-rectifier unit out of service.

12.5.3 DC RAIL POTENTIALS [Future]

12.5.4 RATING OF DC POWER CABLES (AMPACITY) [Future]

SECTION 12.6 - REFERENCES

1. "Westinghouse Distribution Systems Electric Utility Engineering Reference Book", Westinghouse Electric Corporation, East Pittsburgh, PA, 1965, pages 24-25.

2. International Standard IEC 62128-1:2003, *Railway Applications – Fixed Installations – Part 1: Protective provisions relating to electrical safety and earthing*

3. R. W. Stell, "A Review of Current Standards and Codes for Maximum Permissible Rail Voltage Rise on Direct Current Traction Power Systems", March, 2011 IEEE/ASME Joint Rail Transit Conference, Paper JRC2011-56121.

4. R. W. Stell, "Cable Ampacity Tables for Direct Current Traction Power Systems", 2005 APTA Rail Transit Conference.