AREMA

AMERICAN RAILWAY ENGINEERING AND MAINTENANCE-OF-WAY ASSOCIATION

Part 6

Traction Power Supply Requirements for Railroad AC Electrification Systems

— 2021 —

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SECTION 6.1 GENERAL

6.1.1 PURPOSE (2021)

Part 6 of Chapter 33 provides recommendations for study, design, and construction methods for the implementation of modern 60 Hz alternating current (ac) Traction Power Supply (TPS) systems for railroad electrification projects.

Further, the purpose of these guidelines and recommendations is to ensure that the traction power supply systems are designed, manufactured, constructed, installed, and tested to deliver sufficient power to rolling stock and to provide safe, efficient, and continuous operation of the systems under normal and contingency conditions under the environmental conditions prevalent in the project locale.

6.1.2 SCOPE (2021)

The scope of the Part 6 includes new electrification systems for regional commuter rail, intercity rail, intercity high-speed rail, and freight railroad systems considered for operation at electrification voltages recommended in Part 3, Chapter 33; that is, at 12.5 kV ac, 25 kV ac, or 50 kV ac nominal electrification voltage, obtained through transformation of utility ac power at commercial frequency of 60 Hz. It also includes the expansion or modification of existing 25 Hz and 60 Hz ac electrification systems.

Some existing ac electrification systems operate at 12 kV ac nominal electrification voltage and 25 Hz frequency. Construction of new systems at 25 Hz frequency is not recommended as the cost of wayside frequency conversion equipment increases the overall system costs.

Other electrification systems and subsystems, such as the traction power distribution system, the traction power return system, signal system, communications system and rolling stock are discussed only when essential to operation of the traction power supply system.

SECTION 6.2 ELECTRIFICATION SYSTEM LOAD

6.2.1 GENERAL (2021)

Railroad traffic can be broadly divided into two major types, passenger and freight. Passenger rolling stock typically operates with higher acceleration rates than freight rolling stock, and therefore, their power demand is relatively high during acceleration and decreases considerably once the train has attained its normal cruising speed. Freight trains operate with heavy tonnage and at relatively low acceleration rates and their power demand during acceleration and cruising can be of the same order of magnitude.

The train power demand is influenced by factors including train consist size, weight, maximum acceleration, maximum train operation speed, alignment gradients, density of traffic, operating practices and rolling stock propulsion equipment design.

6.2.2 TRACTION POWER DEMAND (2021)

6.2.2.1 Power Demand Characteristics

Power demand of traction power supply systems is significantly different from power demand produced by the usual utility loads. Although there are exceptions, most utility loads change in magnitude relatively slowly, are well distributed amongst the

three phases of transmission and distribution circuits, are nearly sinusoidal, and typically have a high power factor. Occurrence of short circuits is moderate especially on transmission circuits.

The same cannot be said about the traction loads, as they are highly fluctuating and single-phase. Older rolling stock, utilizing thyristor based converters, contains significant harmonics and operates at comparatively lower power factor. Newer locomotives and EMUs, utilizing insulated gate bipolar transistor (IGBT) based converters, are capable of converting braking power to electrical power at the supply voltage and frequency for use by other trains. With utility agreement, any unused energy can be returned to the utility grid. Short circuits occur frequently on electrification systems. Harmonics and power factor in railway systems are discussed in sections 6.2.2.1.3 and 6.2.2.1.4 below.

6.2.2.1.1 Fluctuation

Traction power demand is of a highly fluctuating nature. This is a result of abrupt, impulse-like changes in power requirements of trains as they accelerate and decelerate, as they encounter or leave track grades, and as they enter and leave distribution system feeding sections. The magnitude and frequency of the impulses increase during peak time (rush-hour) periods of operation as longer trains operate at shorter headways. These loads also move across the utility transmission grids as the trains move along the route.

6.2.2.1.2 Phase-to-Phase Connection

AC electrification system traction loads are single-phase and are connected to a utility three-phase system phase-to-phase. The unequal phase loadings of the three phases cause the utility system currents to be unbalanced. The different currents in each phase cause unequal voltage drops in the three-phase utility network and this causes the utility voltages to be unbalanced at the bus. These unbalances require the connection to high voltage transmission circuits rather than distribution circuits.

6.2.2.1.3 Harmonic Content

The train load on the electrification system substations consists of a number of single-car and/or multi-car trains operating simultaneously on the system. The power electronics of the rolling stock propulsion and auxiliary systems generate harmonic currents. It is important that the traction power designers work with the rolling stock designers to ensure compatibility in systems.

Harmonics generated by older thyristor controlled propulsion systems are significant and need to be taken into account in any evaluation of harmonic characteristics of the system if locomotives or EMUs with this technology are proposed to be used. Almost all new locomotives and EMUs are equipped with modern propulsion systems using integrated gate bipolar transistor (IGBT) converters whose harmonics are usually negligible and in many cases can be ignored.

The harmonic currents generated by the rolling stock produce harmonic voltages along the traction power distribution system and inject harmonics into the utility power supply system. If it is found necessary to lower the harmonic content, the installation of filtering equipment on-board the rolling stock and/or at traction power substations is recommended.

6.2.2.1.4 Power Factor

Power factor of older thyristor-controlled propulsion systems is relatively low, especially during acceleration at low speeds, and needs to be taken into account in any load flow evaluations. Modern rolling stock utilizing propulsion systems with IGBT converters can be designed with power factor approaching unity.

6.2.2.1.5 System Faults

Traction power distribution systems are subjected to faults and short circuits in a greater degree than utility power systems. This is mainly due to relatively low overhead system clearances, which are often further reduced under bridges and in tunnels, and due to a relatively large number of support insulators used per mile of the system. System design must be coordinated along the route to mitigate areas at overhead bridges and tunnels to minimize the faults and short circuits.

6.2.2.2 Power Demand Impact

Rapidly varying, single phase traction loads have the following impacts on utility power systems.

Fluctuations. Recurring fluctuations in the traction loads may cause a voltage flicker at the utility bus at the point of common coupling. The flicker may cause light flickering and affect operation of some electronic equipment. Flicker requirements should be ascertained during the design phase and complied with.

Voltage and Current Unbalance. As mentioned in Section 6.2.2.1 above, the single-phase nature of the traction load introduces voltage and current unbalance at the utility bus. ANSI Standard C84.1 specifies the recommended limits of voltage unbalance at the supply bus. Some utilities may require more stringent limits for the traction loads. If there is an existing voltage unbalance at the utility bus, the single phase traction load can be used to mitigate it.

Power Factor. Newer rolling stock using IGBTs operate at or near unity power factor and generally should not be a cause for concern. It is recommended that the power factor requirements of the supplying utility company should be ascertained and complied with.

Harmonics. The rolling stock injects harmonic currents into the traction power distribution system. The harmonic currents result in harmonic current and voltage distortion at the point of common coupling. IEEE Std 529 specifies the recommended limits of distortion at the point of common coupling but some utility companies may require more stringent limits. Also, there could be the possibility of resonance at the capacitor banks of the utility company, if located in the vicinity of point of common coupling.

Short Circuits. The short circuit current may cause electromagnetic interference (EMI) into wayside equipment of railways, voltage dip at the utility bus, and electromagnetic forces in the substation equipment.

It is recommended that utility impact studies be performed during the design phase to determine the effects of the traction load and compliance with the utility requirements. These studies should be coordinated with the requirements of the utility company.

SECTION 6.3 AC ELECTRIFICATION SYSTEM CONFIGURATION

6.3.1 GENERAL (2021)

The major components of any traction electrification system are the traction power supply, the traction power distribution, and the traction power return systems, as briefly described below:

- Traction Power Supply System. The traction power supply system consists of all equipment between the interface point with the local electric power utility company and the interface points with traction power distribution and return systems. The supply system includes traction power substations located at predetermined spacing along the system right-of-way. The substations receive power from the power utility system and supply power to the traction power distribution system. Also included in the power supply system are paralleling stations, autotransformer stations, and switching stations.

- Traction Power Distribution System. The traction power distribution system consists of all equipment between the interface with the traction power supply system and the vehicle pantographs. The distribution system consists of an overhead contact system (OCS) which includes the overhead catenary system, autotransformer feeders (in autotransformer-fed systems), supporting structures, and pole footings or foundations. The system receives power from the substations via overhead feeders or underground cables and supplies the power to the rolling stock.

- Traction Power Return System. The traction power return system consists of all equipment between the interface with the traction power substation return connection point and the vehicle wheels. The return system includes running rails, impedance bonds, cross-bonds, static wire, and natural ground. Current from the traction power

supply system flows through the primary winding of the on-board stepdown transformer before exiting to the running rails via wheels. The rolling stock on-board propulsion system conditions the power received from the secondary winding of the on-board transformer for use by traction motors.

Each of the electrification system components is described in more detail in the following sections.

6.3.2 TRACTION POWER SUPPLY SYSTEM (2021)

6.3.2.1 Utility Power Supply

The traction power substations receive power directly from the high voltage electrical power utility substations located in the proximity of the route or from transmission lines crossing or running along the alignment. Preferable utility system voltage levels are in the range of 115 kV to 230 kV. In areas where the utility system may not have transmission in this range of voltage, consideration can be given to supplying the traction substation at 69 kV or 345 kV.

Connections to the utility high voltage lines are recommended to ensure high supply reliability. The systems below 115 kV are not usually the first choice as the system fault level may be too low causing excessive voltage flicker, phase unbalance, and harmonic distortion that may result from the addition of the highly fluctuating, single-phase, and non-sinusoidal traction load. Using supply at voltages above 230 kV is generally not cost effective due to the considerable additional cost required for traction substation input equipment insulation.

To enhance reliability in the event of a utility supply system outage or maintenance requirements, the traction power substations should be supplied by two high voltage lines which should be as independent of each other as possible.

6.3.2.2 Substation Type and Equipment

The ac substations transform the utility power from high voltage to the ac electrification system utilization voltage. The traction power supply equipment is contained in traction power substations and includes all equipment necessary to transform and control the utility ac voltage to the traction power system ac utilization voltage used by the rolling stock.

The major items of equipment in each substation include high voltage supply line dead-end structures, high voltage circuit breakers, high voltage disconnect switches, traction power transformers, medium voltage switchgear, ac feeder and return cables, raceways, ductbanks and conduits, auxiliary, signal (if required) and communications power supply systems, protective devices, programmable logic controllers, supervisory control and data acquisition (SCADA) systems, instrumentation, indication, annunciation, lighting, temperature control system, busbars and bus connections, control and low voltage wiring, equipment enclosures, insulation and grounding systems, foundations, substation control building housing, and other miscellaneous equipment. The traction power substations may also contain phase balancing equipment, harmonic distortion filters, and power factor correction equipment, if required by the utility impact studies.

Due to the increased electrical clearances required in substations for high voltage equipment the traction power substations are normally outdoor facilities with each component delivered to site separately and installed on previously prepared foundations or footings. Medium voltage switchgear may be installed outdoor or indoor in prefabricated or field constructed buildings. The DC control equipment and batteries are recommended to be installed in prefabricated or field constructed buildings.

6.3.2.3 High Voltage Circuit Breakers and Disconnect Switches

The function of the high voltage circuit breaker is to disconnect the traction power transformer from the utility system following a fault, severe overload condition, or for maintenance. Each high voltage circuit breaker should be equipped with disconnect switches on either side, which have appropriate grounding provisions, to provide a visible isolation of the circuit breaker and protection during maintenance.

6.3.2.4 Traction Power Transformers

The high voltage utility power is transformed to the distribution voltage by traction power transformers. Normally, each substation is equipped with two equally-sized transformers to allow continuous system feeding in the event of a power outage

of one of the utility feeder, or of a transformer, or other item of high voltage equipment. Traction power transformers may require designs incorporating extra bracing due to the high number of short circuits.

The single-phase traction power transformer primary windings are connected to two phases of the utility power system. Because power is being drawn from only two phases of a three-phase system, a certain amount of current and voltage unbalance will occur. In order to mitigate the effects of the unbalanced currents and voltages, the single-phase connections should be coordinated with the utility and alternated at successive transformers. Therefore, in an interconnected power network, the unbalanced currents and voltages will tend to balance out by the time they reach the nearby utility substation or generators. In the event of pre-existing unbalance on the utility bus, the transformers should be connected to the phases so as to reduce the existing unbalance - see 6.2.2.2 above.

6.3.2.5 Medium Voltage Switchgear

Each traction power substation includes a lineup of ac switchgear to distribute power to the OCS, auxiliary power supply transformers, and substation special equipment, if installed. The switchgear should be configured to include a main secondary side circuit breaker for each transformer, a busbar with a bus tie circuit breaker, and feeder circuit breakers. The function of the main breaker, together with the high voltage circuit breaker, is to disconnect the traction power transformer from the system following a fault, severe overload condition, or for maintenance.

Power to the OCS is supplied via catenary and autotransformer feeder (if an autotransformer-fed system is used) circuit breakers. The function of the circuit breakers is to protect the overhead distribution system against short-circuit and to enable system outages for maintenance purposes. It is recommended to equip each track and each autotransformer feeding direction with its own dedicated circuit breakers. Thus, for a two-track system operating in the east-west direction, the following catenary and autotransformer feeder circuit breakers would be required:

- Track 1 east — Feeder 1 east
- Track 1 west — Feeder 1 west
- Track 2 east — Feeder 2 east
- Track 2 west — Feeder 2 west

Additionally, it is strongly recommended that a dedicated circuit breaker and alternate source should be used to supply the rolling stock maintenance facility, if the facility is large and/or located nearby or is at the end of the electrification system.

The substation auxiliary system can be protected by fuses or circuit breakers. Substation special equipment, such as phase balancing equipment, harmonic filters, or power factor correction equipment should be connected to the substation busbar via circuit breakers or circuit switchers.

The busbar needs to be equipped with a bus tie circuit breaker. The bus tie circuit breaker is normally open and is closed only when two adjacent sections of the distribution system need to be connected in the event of a traction power transformer outage.

6.3.2.6 Special Equipment

Depending on the system and rolling stock circumstances, the need for special equipment should be determined in consultation with the utility company based on the utility impact studies. The substations may need to be equipped with additional, special, equipment which may include:

- Balancing Equipment - to limit the voltage unbalance at the utility bus
- Harmonic Filters - to limit the harmonic effect to the power utility system at the point of common coupling and other systems such as signaling and communications systems
- Power Factor Control Equipment - to control the power factor at the point of common coupling or at the point of utility metering

6.3.3 TRACTION POWER DISTRIBUTION SYSTEM (2021)

6.3.3.1 Distribution System Configuration

Modern ac railroad electrification systems are recommended to use the following configurations of the distribution systems:

- Direct-Fed System (DF) operating at 12.5 kV, 25 kV or 50 kV electrification voltages, single-phase, ac, at the commercial frequency of 60 Hz, as shown in Figure 33-6-1.
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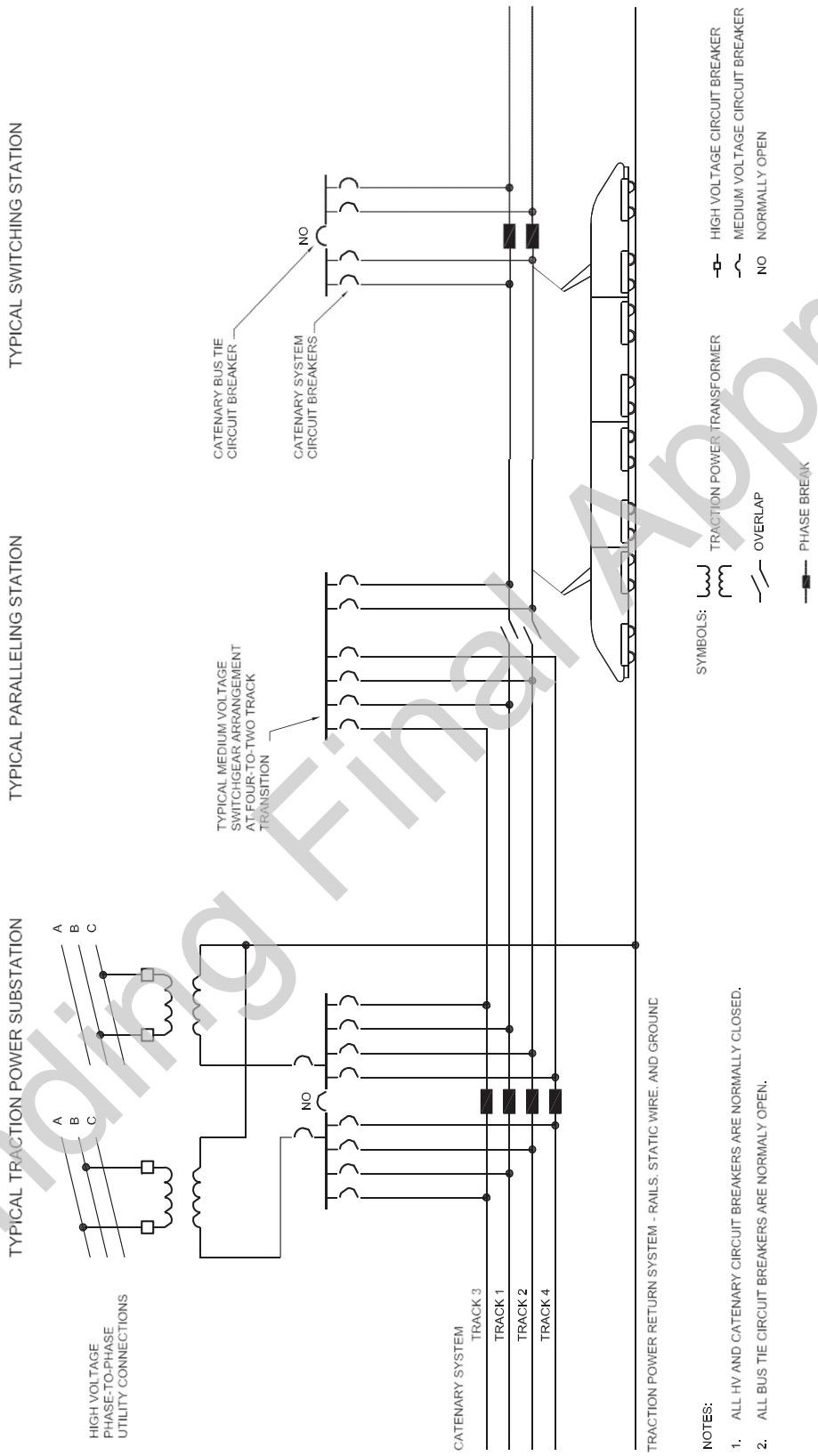

Figure 33-6-1. Typical Direct-Fed AC Traction Power System - Simplified One-Line Diagram

- Feeder Booster Transformer System (BT) operating at 12.5 kV, 25 kV or 50 kV electrification voltages, single-phase, ac, at the commercial frequency of 60 Hz, as shown in Figure 33-6-2.

- Autotransformer-Fed System (ATF) operating at 2 x 12.5 kV or 2 x 25 kV electrification voltages, single-phase, ac, at the commercial frequency of 60 Hz, as shown in Figure 33-6-3.

6.3.3.2 Direct-Fed System

System Connection. In the direct-fed system, traction power from substations is distributed to trains by the catenary system. The catenary system is connected through medium voltage switchgear to one end of the substation transformer secondary winding. The other end of the winding is solidly connected to the rail/static wire/ground return system.

Phase Breaks. Since each traction power transformer primary winding is connected to different phase pairs, the secondary windings of adjacent transformers are out-of-phase. In order to electrically separate the sections of distribution system operating at different phases, phase breaks are installed in the catenary system at the substations and at approximately the midpoint between substations.

Switching Stations. In order to provide switching for the catenary system in the event of substation outages, switching stations are provided at the substation midpoint phase break locations. To facilitate the overhead system switching operations, each switching station is equipped with medium voltage switchgear. The switchgear is configured to include catenary circuit breakers on each side of the phase break and a bus tie circuit breaker. The catenary circuit breakers are normally closed and the bus tie circuit breaker is normally open. The purpose of the bus tie breaker is to connect the adjacent sections of the distribution system in the event of a substation outage. Voltage across the open contacts of the bus tie circuit breakers may be more than the nominal system voltage, as much as two times, depending upon the phase selection.

Paralleling Stations. Where substation to switching station spacing is large, and at the end of an electrified line, the distribution system may be equipped with paralleling stations. Each paralleling station is equipped with medium voltage switchgear in a similar configuration to that in switching stations. However, since the catenary voltage on either side of the paralleling stations is of the same phase and magnitude, bus tie circuit breakers and phase breaks are not required.

Benefits of Paralleling Stations and Switching Stations. The switchgear in switching and paralleling stations enables sections of the distribution system to be disconnected following a fault and for maintenance. The switchgear is configured to permit paralleling of the overhead distribution system conductors in multiple track areas. The conductor paralleling decreases the effective system impedance between substations and trains and improves the voltage profile along the system. The paralleling also provides for better current sharing between conductors of adjacent tracks and improves system fault detection.

6.3.3.3 Booster Transformer System

Booster transformers were used in the direct-fed system to reduce electromagnetic interference (EMI) in the adjacent communication and low voltage circuits. The system, however, has not been used in recent years, as more and more communications circuits are replaced by fiber optic cables and other systems immune to EMI. Booster transformers are 1:1 current transformers installed between the catenary system and the return circuit at insulated overlaps along the distribution system, usually at 1.5-2 mile spacing - see Figure 33-6-3.

The purpose of the booster transformers is to cause the catenary and return currents to flow as closely as possible to each other to cancel their external effects and reduce the EMI with wayside equipment. The higher number of booster transformers yields higher level of mitigation, but impedance of the distribution system correspondingly increases. The position of the return feeder can be selected for greatest mitigation effects.

6.3.3.4 Autotransformer-Fed System

System Connection. In the autotransformer-fed system, traction power from substations is distributed to trains by overhead autotransformer feeder and catenary systems. The autotransformer feeder system is connected to one end of the substation transformer secondary winding and the catenary system is connected to the other end of the winding through medium voltage

switchgear. The secondary winding of the transformers is provided with a center tap, which is tied to the rail/static wire/ground return system. In some cases, the main transformer secondary winding is not provided with an externally accessible mid-point. In such cases, the rail/static wire/ground system may be connected to the midpoint of the autotransformer(s) either located within or close to the traction power substation.

Normally, one autotransformer feeder is provided for each track. However, a maximum of two autotransformer feeders may be sufficient for multi-track railroad alignments.

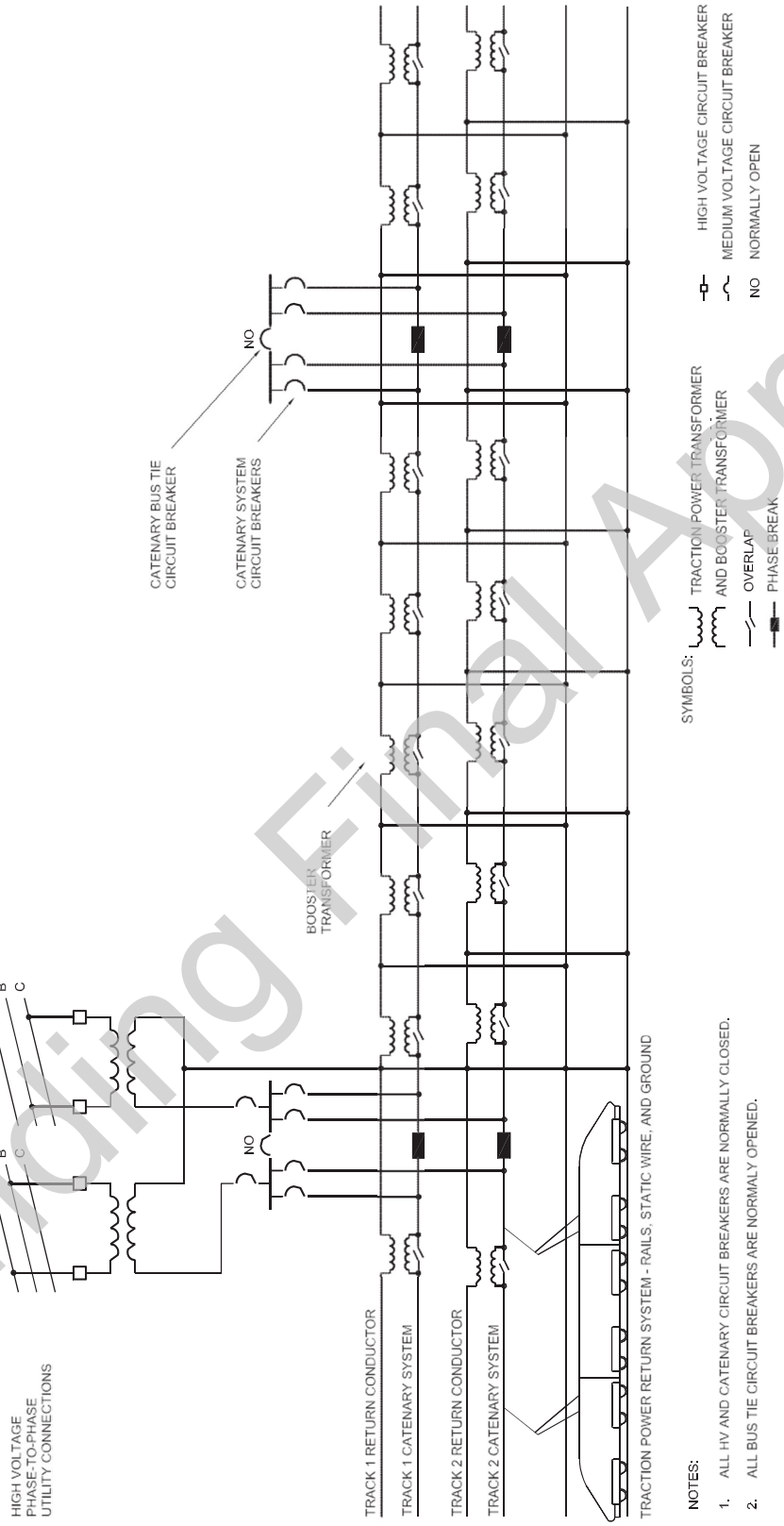

Figure 33-6-2. Typical Direct-Fed AC Traction Power System with Booster Transformers - Simplified One-Line Diagram

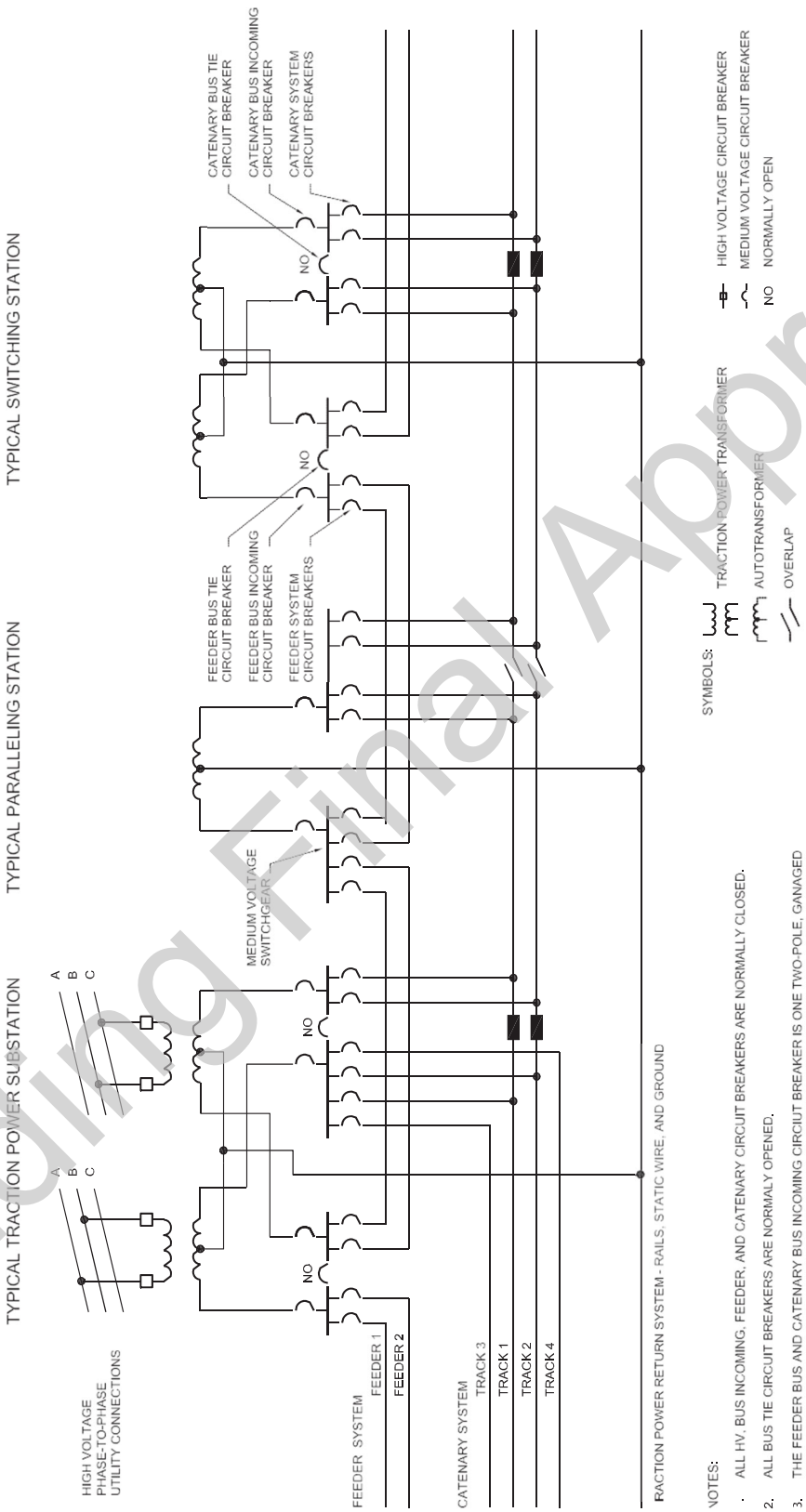

Figure 33-6-3. Figure 33-6-3.Typical Autotransformer-Fed AC Traction Power System - Simplified One-Line Diagram

Phase Breaks. Since each traction power transformer primary winding is connected to different phase, pairs the secondary windings of adjacent transformers are out-of-phase. In order to electrically separate the sections of distribution system operating at different phases, phase breaks are installed in the overhead catenary system at the substations and at approximately the midpoint between substations. The autotransformer feeder is sectioned at the same location using insulators.

Switching Stations. In order to provide for switching of the autotransformer feeder and catenary system in the event of substation outages, switching stations are provided at the substation midpoint phase break locations. To facilitate the overhead system switching operations, each switching station is equipped with medium voltage switchgear. The switchgear is configured in two sections. The autotransformer feeder section includes circuit breakers on each side of the sectionalizing point and a bus tie circuit breaker. Similarly, the catenary section includes circuit breakers on each side of the phase break and a bus tie circuit breaker. The autotransformer feeder and catenary circuit breakers are normally closed and the bus tie circuit breakers are normally open. The autotransformer feeder and catenary circuit breakers are recommended to be arranged to operate mechanically and electrically together. The purpose of the bus-tie breakers is to connect the adjacent sections of the distribution system in the event of a substation outage. Some electrification systems use two-pole circuit breakers in place of separate breakers for the catenary and autotransformer feeder circuits. In this case, the catenary and autotransformer feeder will be de-energized simultaneously in the event of a fault on either the catenary or the autotransformer feeder.

Paralleling Stations. In the autotransformer-fed system substation to switching station spacing is often large, and therefore, the distribution system may be equipped with a number of paralleling stations installed between the substation and the switching station. At the end of an electrified line, the distribution system may be equipped with paralleling stations to improve the voltage profile along the system. Each paralleling station is equipped with medium voltage switchgear in a similar configuration to that in the switching stations. However, since the autotransformer feeder and the catenary voltages on either side of the paralleling stations are of the same phase and magnitude, there is no need for a bus tie circuit breakers or phase breaks.

Benefits of Paralleling Stations and Switching Stations. The switchgear in the switching and the paralleling stations enables sections of the distribution system to be disconnected following a fault and for maintenance. The switchgear is configured to permit paralleling of the overhead distribution system conductors in multiple track areas. The conductor paralleling decreases the effective system impedance between substations and trains and improves voltage profile along the system. The paralleling also provides for better current sharing between conductors of adjacent tracks and improves system fault detection.

Autotransformers. In the autotransformer-fed system, traction power to the catenary-rail system is delivered from the autotransformer feeder- catenary system distribution via autotransformers, and therefore, autotransformers are required to be installed at each paralleling and switching station, spaced approximately 6-10 miles apart as determined by load flow studies for the system. The autotransformer winding ratio must correspond to the distribution voltage (autotransformer feeder-to-catenary) and the traction voltage (catenary-to-rail) ratio. Most new systems use 2:1 ratio, i.e. 50 kV between the autotransformer feeder and catenary and 25 kV between the catenary and rails for a 25 kV nominal electrification system. Some existing systems use 3:1 ratio; i.e., 36 kV between autotransformer feeder and catenary and 12 kV between catenary and rails.

For example, using an autotransformer ratio of 2:1, two system alternatives are possible:

- 2 x 12.5 kV resulting in the following system voltages:
  - 25 kV between the autotransformer feeder and the catenary systems
  - 12.5 kV between the autotransformer feeder system and the rail/static wire/ground return system
  - 12.5 kV between the catenary and the rail/static wire/ground return system
- 2 x 25 kV resulting in the following system voltages:

- 50 kV between the autotransformer feeder and the catenary systems
- 25 kV between the autotransformer feeder system and the rail/static wire/ground return system
- 25 kV between the catenary and the rail/static wire/ground return system

The autotransformer-fed system enables power to be distributed along the system at higher than the train utilization voltage. For example, in the 2 x 25 kV autotransformer-fed system power is distributed at 50 kV while the trains operate at 25 kV. This arrangement results in lower voltage drop along the system than would be possible with the 25 kV direct-fed system. This lower voltage drop improves the voltage profile along the line and permits greater substation spacing, and consequently, a lower number of substations than would be possible with the direct-fed system.

An important advantage of the autotransformer feed is that, since the current in the autotransformer feeder flows in the opposite direction to the current in the catenary, it mitigates the effects of electromagnetic interference with other wayside equipment or circuits, as discussed in the Booster Transformer system – see Section 6.3.3.3.

6.3.4 TRACTION POWER RETURN SYSTEM (2021)

6.3.4.1 Return System Conductors

The trains collect propulsion power from the OCS using pantographs and return the current back to the substations via a traction power return system. The traction power return system for an ac railroad electrification consists of the running rails, impedance bonds, cross-bonds, overhead static wires, return conductors, autotransformer feeders (in autotransformer-fed systems), and the ground itself. Normally, both running rails of each track serve as return conductors, except at special trackwork locations, and around expansion or track switches, where electrical continuity should be provided by jumper cables. The running rails should be welded in continuous lengths and any bolted joints must be electrically bonded.

In order to enable both rails to carry the return current and to maintain the double rail signaling track circuits commonly used by North American railroads, any existing track circuits and impedance bonds should be replaced with those compatible with the ac electrification system when electrifying an existing railroad and placement coordinated with the signal engineering.

6.3.4.2 Return System Continuity and Grounding

In a direct-fed system, the return system interfaces with the traction power supply system at the traction power substations only, where the neutral (or ground) end of the secondary winding of the traction power transformer is connected to rails/static wire/ground. In an autotransformer-fed system, the return system interfaces with the traction power supply system at traction power substations, autotransformer stations, and switching stations, where the neutral (or ground) end of the transformer secondary or the autotransformer windings is connected to the rails/static wire/ground. Selection of the location of the return connection to the rails requires coordination with the signal department.

At locations requiring insulated joints, the electrical continuity of the return system should be maintained by use of impedance bonds - refer to Part 5 of this Chapter. The running rails should be cross-bonded and grounded for traction power return current equalization and rail potential control through impedance bonds at every transformer and autotransformer location and as required by the design of the signal or train control systems. The cross-bonds are periodically connected to the static wire which interconnects the OCS supporting structures. The static wire is grounded at frequent intervals. The result is that a portion of the return current flows in the rails, the static wire, and the ground.

The purpose of this design is to provide a return system with as low an impedance as possible to limit voltage rise along the rails (rail-to-ground potentials), and to improve catenary fault detection by creating sufficiently high short-circuit currents.

Particular attention should be paid to return system grounding arrangements at, and in the vicinity of, passenger stations to avoid undesirable voltage rise between the station metallic structures and trains – refer to Part 7 of this Chapter.

The cross bond grounding must be coordinated with the signaling system design, refer to Part 5 and Part 7 of this Chapter.

6.3.5 NORMAL AND CONTINGENCY OPERATION (2021)

6.3.5.1 Continuity of Supply

The power supply, distribution, and return systems should be designed so that adequate propulsion power continues to be supplied to the system under normal and contingency operations. Therefore, electrical continuity must be provided in the distribution system from substation-to-switching station under normal operating conditions and under single traction power transformer outage. Electrical continuity must be provided from substation-to-substation under full substation outage conditions. At the substations, paralleling stations, and switching stations, the distribution system continuity is provided by the normally closed catenary, and autotransformer feeder (for autotransformer-fed systems) circuit breakers. In the event that a circuit breaker needs to be opened for repair or maintenance continuity can be provided by:

- Provision of hand-operated or motor-operated bypass disconnect switches
  or
- Provision of a transfer bus and an additional circuit breaker which can substitute for any circuit breaker via the transfer bus

The distribution system should be sectionalized into electrical sections to limit the length of the track to be de-energized following a fault or for system maintenance. The sectioning can be performed at substations, paralleling stations, and switching stations, as well as at interlockings where crossovers and turnouts are installed - refer to Part 4 of this Chapter. Care must be taken when there are multiple interlockings between substations and switching stations.

6.3.5.2 Normal Operation

During normal operation of the power system, i.e., when all major components of the system, such as substation transformers, feeders, and autotransformers, are in service, rated train operating performance during peak-hour traffic conditions should be maintained. This includes providing full performance train voltage levels to allow simultaneous starting of trains.

6.3.5.3 Contingency Operation

Normally, each traction power transformer is feeding its own section of the system. During a substation transformer outage, continuity of supply to that section is achieved by immediate closing of the substation bus tie circuit breaker. The remaining substation transformer then feeds both sections of the system.

Each traction power transformer in a substation is recommended to be supplied by an independent transmission line. In this event, an entire substation failure is unlikely. Nevertheless, provision for such a contingency should be made in the system design. Following an outage of an entire substation, the two neighboring substations should maintain continuity of supply. These substations must be capable of supplying their own sections of the system as well as the adjacent sections previously supplied with the now out-of-service substation. This is facilitated at switching stations situated on either side of the out-of-service substation. During the substation outage, the normally open switching station bus-tie breakers are closed, thus extending the supply area of the two neighboring substations in operation. The bus-tie breaker in the out-of-service substation remains open to separate the two supplies at different phases

When a substation at the end of the system is out-of-service, the end-of-the-line is supplied from the closest operating substation by closing bus tie circuit breakers in the switching station and the out-of-service substation.

In the event of an outage of one traction power transformer, feeder, or autotransformer, the system should operate at near-full performance. For multiple contingencies, system performance restriction of the rolling stock should be expected. This can result in lower acceleration rate of trains, possible lower maximum speed of operation, and increased trip time.

SECTION 6.4 ELECTRIFICATION SYSTEM SELECTION

6.4.1 SYSTEM CONFIGURATION (2021)

There are several different traction power systems. The direct-fed system provides simplicity by comparison with the

autotransformer-fed system and the booster transformer system. The substations, paralleling stations, and switching stations require switchgear for the catenary system only. However, due to feeding limitations Direct-Fed systems may require additional substations.

Booster transformers are utilized mainly to mitigate electromagnetic interference. However, the booster transformers and along-track return circuit feeders increase the system complexity and cost. Further, the impedance of the distribution system is higher, often resulting in the need for more substations. The booster transformer system has not been used in recent years, since the overhead communication circuits in the vicinity of railroad tracks have been replaced by underground circuits and/or fiber optic cables.

The autotransformer-fed system requires overhead, along-track, autotransformer feeders and switchgear for the catenary system and the autotransformer feeders in all substations, paralleling stations, and switching stations. Additionally, all switching stations and paralleling stations are equipped with autotransformers. The autotransformer-fed system is generally used for high traffic density and high speed routes and minimizes the number of main traction power substations.

6.4.2 SUBSTATION SPACING (2021)

Substation spacing depends on the train headways, train consist sizes, alignment characteristics, operation practices, and the traction power supply, distribution and return system configurations. To determine the substation spacing, a computer-aided load-flow simulation of the traction electrification system should be performed. Normally, a number of computer studies are performed to simulate the electrification system under various operating scenarios and to optimize the system design parameters.

The typical substation spacing for a 25 kV ac direct-fed system is approximately 15 to 20 miles, and for a 50 kV ac direct-fed system is approximately 30 to 40 miles.

The booster transformers introduce impedance into the distribution system, and therefore, the substations need to be spaced at shorter intervals than is possible with the direct-fed system, typically 10 to 15 miles apart for a 25 kV system.

The autotransformer-fed system arrangement permits longer substation spacings relative to the direct-fed system which is advantageous in areas where locations of utility power input are limited. Typical substation spacing for a 2 x 25 kV ac autotransformer system is 30 to 40 miles.

6.4.3 ELECTRIFICATION VOLTAGE (2021)

The 25 kV ac and 50 kV ac electrification voltages should be considered first for the design of new ac electrification systems. In alignments with numerous low overhead clearance obstructions, 12.5 kV ac voltage can be evaluated. However, the 12.5 kV voltage is usually only selected when expanding an existing system electrified at this voltage.

Generally, electrification at the higher voltages is more cost effective then at the lower voltages. The higher electrification voltage results in lower distribution system currents and lower voltage drops along the system. Substations can be spaced further apart and/or distribution system conductors of lower cross-sectional area can be selected.

The higher electrification voltages, however, require increased clearances between conductors and grounded structures. This is an important consideration in areas of low clearance bridges and in tunnels. Cost of any required civil modifications needs to be always compared to the savings obtained in the traction power supply and distribution systems.

6.4.4 UTILITY POWER AVAILABILITY (2021)

Availability of utility power connections to substations should be considered when selecting the system type and electrification voltage.

For ac electrification system, high voltage substations or transmission lines are required to supply power to the traction power substations. Since such transmission systems are not always available along the potential rail alignment, the substation locations are often governed by the locations of power utility high voltage substations, transmission lines, or high voltage cables.

During the preliminary design of any electrification project the power utility should be contacted at an early stage of the substation location effort. The input required from the utility company includes substation power supply availability, transmission feeder availability, spare capacity, required utility impact studies, and short circuit fault levels for the potential supplies in areas considered for traction power substations locations.

6.4.5 ELECTROMAGNETIC INTERFERENCE (2021)

The electrification systems currents can cause electromagnetic interference (EMI) with other subsystems and equipment along the wayside. This is due to the rapidly fluctuating currents containing harmonic frequencies in the traction power substations, the distribution system conductors, and the vehicles. The overall electrification system EMI levels need to be limited to protect the system itself and the wayside facilities, including signaling circuits, communications circuits, and equipment adjacent to the system right-of way from the
potentially harmful effect of the EMI.

The EMI from a traction power substation is localized and usually does not present a significant problem. The EMI from the distribution system is usually more significant. Since the distribution system extends for many miles, the electromagnetic induction and its possible adverse effects are a function of the magnitude of the disturbing current and the length of exposure. The EMI from rolling stock may affect the signaling, communications and other wayside equipment as it transverses the route.

In the direct-fed system, all traction power supply and return currents are flowing from the substations along the entire substation-to-switching station length. In the autotransformer-fed system, the traction power supply and return currents tend to be confined between the much closer-spaced adjacent paralleling station/switching station pair in which the train is currently located.

The substation-to-switching station length in the direct-fed system is usually significantly longer than the spacing between adjacent paralleling stations and switching stations in the autotransformer-fed system. Therefore, since the traction current flows over greater distances in the direct-fed system than is the case in the autotransformer-fed system, there is a likelihood of higher electromagnetic induction and possible interference into wayside facilities with the direct-fed system than is the case with the autotransformer-fed system.

Additionally, the electromagnetic interference in the autotransformer-fed system is reduced by the presence of the autotransformer feeder. As the currents in the autotransformer feeder and catenary systems are 180° out-of-phase, the currents in the two conductors travel in opposite directions, and the electromagnetic fields of the conductors cancel each other out and contribute to significantly lower levels of EMI.

In the direct-fed system the booster transformers can be considered to mitigate the EMI in circumstances where other EMI reduction is not effective due to special local conditions.

6.4.6 RAIL POTENTIAL(2021)

Rail potential, relative to remote ground, is a function of the magnitude of the return current, the rail resistance, rail-to-ground leakage resistance, and the distance between the locations where the rails are grounded via impedance bonds, often called A-points (see Part 5). Increased rail potentials cause increased voltages between rolling stock and station platform, and possible discomfort for passengers boarding the trains.

In the direct-fed system all traction return currents from trains flows back to the substations along the entire substation-to-switching station length. In the autotransformer-fed system, the return current from trains flows between the much closer-spaced paralleling stations and switching stations.

Leakage of part of the current from the rails to ground can be often ignored for the purpose of rail potential rise calculation to err on the safe side although it contributes to limit the rail potential rise. Since the voltage rise along the rails is a function of the magnitude of the return current and the length of current flow, the potential rise along the rails is determined by the distance between the locations where rails are connected to ground. The rail potential rise can be minimized by reducing the distance between the grounded cross-bond locations, with due consideration to broken rail protection. Final configurations

must be coordinated with railroad signaling engineers.

6.4.7 ACHIEVING COST EFFECTIVE ELECTRIFICATION SYSTEM DESIGN (2021)

During a typical preliminary design effort, the substation, paralleling station, and switching station locations are adjusted, the traction power transformer and autotransformer ratings modified, and the size of the distribution conductors changed to obtain optimum performance of the overall system

For example, longer substation spacing will result in lower train voltages along the distribution system, higher currents in the distribution system, and higher substation power demands. Alternatively, shorter substation spacing will result in higher train voltages along the distribution system, lower currents in the distribution system, and lower substation power demands. Locations of suitable utility feed points and available real estate are factors that also must be considered.

The most satisfactory and suitable combination of the technical parameters and the most economic design is achieved by conducting system studies. The studies should evaluate the traction power system performance, its impact on the serving utility, and its impact on the existing wayside facilities that may or may not belong to the railroad.

Often, an iterative process needs to be employed. In this process, an initial system design is studied first, and if system performance objectives are not met, adjustments to the system parameters are made, and the system performance is examined again with the new parameters. Frequently, several repeats of the system studies are required to obtain the most desirable combination of technical parameters at the lowest overall system cost.

SECTION 6.5 SYSTEM STUDIES

6.5.1 GENERAL (2021)

The system studies described in this section are recommended to be performed for each new electrification system design and for major extensions and modifications of existing systems. The studies should be performed at various stages of design as discussed.

6.5.2 TRAIN OPERATION SIMULATION AND LOAD-FLOW STUDY (2021)

The purpose of train operation simulation and load-flow study is to confirm the adequacy of the overall traction electrification design to facilitate train operations during normal and contingency operations. The study should also include yard and maintenance facility loads which are often located at the end of the line. The design should define the locations of traction electrification system facilities and the ratings of major items of equipment, such as circuit breakers, transformers, underground cables, and distribution system conductors. As a minimum, the output of the study should include the voltage profile along the alignment, currents in the distribution system conductors, and substation transformer power demands. It is recommended that the study be performed with and without the use of regenerative braking on the vehicles. Return of unused regenerative power to the power utility grid should be discussed and agreed with the utility. This study is recommended to be performed during preliminary design.

6.5.3 DISTRIBUTION SYSTEM CONDUCTOR TEMPERATURE STUDY (2021)

The distribution system conductors of appropriate sizes and materials need to be selected to deliver sufficient power to the rolling stock without causing excessive voltage drop along the electrification system and without conductor overheating. Based on the distribution conductor currents developed in the Traction Power System Load-Flow Study, the conductor temperature profile versus time should be developed and the maximum temperature achieved compared with the conductor manufacturer's recommendation. Comparison of the conductor ampacity to the current RMS value is not considered sufficiently accurate. The study is recommended to be performed during preliminary design along with the load flow study.

6.5.4 EMI STUDY (2021)

Each electrification project is likely to require some investigation into the impact of electromagnetic interference. The rolling stock, systems components, and equipment along the electrified railroad right-of-way can be subjected to potentially harmful inductive and conductive interference. A comprehensive system-wide compatibility study should be performed for every new electrification project. The study should take into account the characteristics of the rolling stock and the systems equipment, estimate the electromagnetic interference on the traction electrification system, the signal system, the communications system, and the fare collection system, and make recommendations for mitigating the same.

Concerns have also been raised regarding harmful effects of electromagnetic fields on humans. No conclusive research has proved this to be an issue and at the present time, the United States has no national standards which establish acceptable limits of electromagnetic field strengths. Several states have adopted guidelines and regulations and these should be followed in states where electrification is planned. Also, it is recommended that the designer follows guidelines established by other professional or regulatory organizations, such as the World Health Organization (Environmental Health Criteria), the International Non-Ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA), and the American Conference of Governmental Industrial Hygienists (ACGIH).

This study is recommended to be initiated during the preliminary engineering effort and should be periodically updated throughout the project duration. A study following introduction of revenue service is recommended using the same procedures as the baseline study. Comparison of the studies may be used for evaluation of need for any additional possible EMI mitigation measures.

6.5.5 VOLTAGE FLICKER STUDY (2021)

When traction power substation connection points to the power utility system are evaluated, a utility voltage flicker study is recommended. The study should determine the response of the utility system to the fluctuating traction loads and verify the utility system capability to satisfactorily supply the electrification system. It should be noted that the load fluctuations in actual operation may not be as repetitive as used in the study. Note most load flow programs use typical values for acceleration of the vehicles. Actual acceleration by individual train operator may vary due to system operations or constraints. This study should be performed during the preliminary design stage of the project.

6.5.6 PHASE UNBALANCE STUDY (2021)

A single-phase traction load introduces unbalance currents in the three-phase utility system. Resultant unbalance voltage drop causes voltage unbalance at the utility bus. Unbalance voltage negative sequence current flows in power generators and three phase motors. These currents produce additional heating in the machine rotors. Therefore utility companies require limits on the voltage unbalance at the point of common coupling.

ANSI C50.13 and NEMA MG-1 standards cover continuous and short time negative sequence current capability for cylindrical rotor synchronous generators. Rotating machines should withstand the effects of continuous negative sequence current of 5-10 % of rated stator current without injury. On a short time basis, the magnitude of product I_2 t should not exceed 40 for motors, hydraulic turbine or engine driven generators, 30 for indirectly cooled turbine generators, 10 for directly cooled generators up to 800 MVA and 5 for some very large machines, e.g. 1,600 MVA. I_2 is the negative sequence current in per unit of machine rated current and t is time in seconds.

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Recommended voltage unbalance limits at the utility bus are specified in ANSI C84.1. However, the unbalance limits should always be agreed with the power utilities. For example, in a recent railroad electrification study in the USA, the following limits were used:

- Voltage unbalance at the point of substation connection to power utility: 3%
- Negative sequence current in generators: 5%

In some cases, the utility bus voltage may have existing unbalance. In such cases, the traction load can be used to mitigate the existing unbalance on the utility bus.

A utility impact study is recommended to be performed during preliminary design to study the effect of the single phase traction load on the utility system. Power factor analysis is also normally included in the study. Comparisons of the study results with the accepted limits will reveal whether the system phase unbalance is acceptable. In the event that the voltage and current unbalance exceeds the accepted limits, the unbalance can be reduced by allocating power feeding to alternate phases of the supply system at successive substations and by the use of phase balancers. Alternatively, the use of Scott connection circuits may be considered. This study should be performed during the preliminary design stage of the project.

6.5.7 HARMONIC DISTORTION AND SYSTEM RESONANCE STUDY (2021)

Power control equipment on board rolling stock causes harmonic current flows which cause harmonic voltage drops in the system, and distortion at the utility system bus. Harmonic currents in the OCS may also induce noise in control, telecommunication, and signal circuits. In systems with appreciable susceptance in the vicinity of the utility supply bus, some harmonics may coincide with the natural frequency of the system and cause system resonance which will in turn produces additional distorted currents and voltages.

IEEE Std 519 recommends the maximum permissible limits for individual single harmonic distortion and total harmonic distortion (THD) at the point of common coupling. It is recommended that the IEEE Std 519 distortion limits recommendations are followed with the power utility agreement.

Comparisons of the study results with the accepted limits will reveal whether the system current and voltage harmonic distortion are acceptable. In the event that the harmonics at the point of coupling exceed the accepted limits, they can be improved by the application of on-board or wayside filter circuits. If wayside harmonic filters are required, these are normally provided on the 25 kV bus at the TPSSs. When modern rolling stock with IGBT drives is used, the harmonics are likely to be low and the actual necessity for such measures is regarded as rare. This study should be performed during the preliminary design stage of the project. Designer needs to coordinate efforts with the rolling stock designers on new systems.

Phase unbalance and harmonic distortion studies can sometimes be combined in a utility impact study.

6.5.8 SHORT CIRCUIT STUDY (2021)

Short circuit study should be performed during preliminary design to select appropriate impedance of traction power transformers and short circuit current interrupting capability of wayside circuit breakers and switchgear. Further, results of the study are used for ground grid design, an arc-flash hazard study, and a protective device coordination study.

6.5.9 ARC-FLASH HAZARD STUDY (2021)

Arc-flash hazard study on substation and wayside switchgear should be based on the short circuit study. The study should determine calculated incident energy at various distances from the equipment and identify the calculated flash protection boundaries. The study should include requirements of OSHA 29 CFR, NFPA 70E, NEC and IEEE Std 1584 and should provide recommendation on personnel protective equipment (PPE) and appropriate labeling of equipment. The study should be performed during the final design stage of the project.

6.5.10 INSULATION COORDINATION STUDY (2021)

An overall system insulation coordination study is recommended to be performed for each new electrification system design. The study should be performed to determine the protection required for the rolling stock, the traction electrification system, the signal system, the communications system, and the fare collection system from excessive overvoltages primarily caused by lightning strikes and switching surges. The study is recommended to be performed during the design phase of a project.

6.5.11 GROUNDING DESIGN STUDY (2021)

A grounding study is recommended to be performed for the new electrification systems. The study should determine the requirement of ground grid design at each traction power facility and other site specific susceptible locations, such as over-bridges and passenger stations to limit the step and touch potentials within acceptable limits and adequacy of grounded impedance bond locations for acceptable rail potentials. See Part 7 of this Chapter - Traction Electrification System Grounding and Bonding.

6.5.12 PROTECTIVE DEVICE COORDINATION STUDY (2021)

The protective device coordination study should ensure that all protective relays are selected, applied, and set to disconnect faulted equipment out of the circuit following a short circuit without affecting any healthy equipment. The study is recommended to be performed during the final engineering phase of a project.

6.5.13 ATMOSPHERIC CORROSION CONTROL STUDY (2021)

The purpose of the atmospheric corrosion control study is to protect the railroad systems and their surroundings from atmospheric corrosion impact which can cause failure, increased maintenance costs, and reduced aesthetics. The study is recommended to be performed during the design phase of a project. The impact of the ac electrification, if any, on the adjacent infrastructure is also recommended to be studied.

6.5.14 GEOTECHNICAL STUDY (2021)

Soil conditions along the right-of-way should be determined by using existing known data. The purpose of the study is to determine the locations and number of soil borings required for design of foundations and footings for the system facilities.

SECTION 6.6 SYSTEM DESIGN

6.6.1 FUNCTIONAL REQUIREMENTS (2021)

The traction electrification system equipment should be designed for a minimum functional life expectancy of thirty (30) years. Also a Quality Assurance/Quality Control (QA/QC) plan in compliance with ISO-9001 should be established and followed in all phases of system design. During the design stage, the quality of work should be monitored by performing reviews of submittals and conducting design review meetings.

All traction electrification system equipment should be designed to maintain sufficient voltage levels at the rolling stock current collection devices without overloading and overheating of any of the system equipment.

The design must take into account the effects of the highly fluctuating pattern of the traction current, the phase-to-phase utility connections, the frequent distribution system faults, and the harmonic content and power factor of the traction loads to ensure compliance with the utility company requirements and to minimize impact on the wayside equipment.

The overall system insulation should be coordinated to ensure that the voltage surges caused by lightning strikes to the system and circuit breaker switching operations do not damage the system equipment.

The systems must not cause electromagnetic interference affecting wayside signal and communications circuits. The traction

electrification system design must be compatible with the other systems, including the signal, communication, and fare collection systems.

6.6.2 STANDARDS, CODES, AND REGULATIONS (2009)R(2021)

All design work, material selection, installation, testing, and construction should conform to, or exceed, the requirements of the latest editions of standards and codes issued by the following organizations:

Aluminum Association of America	AAA
American Hot Dip Galvanizers Association	AHDGA
American Institute of Steel Construction	AISC
American Iron & Steel Institute	AISI
American National Standards Institute	ANSI
American Society of Mechanical Engineers	ASME
American Society for Testing & Materials	ASTM
American Welding Society	AWS
Association of American Railroads	AAR
Building Officials Conference of America	BOCA
Construction Specifications Institute	CSI
Illuminating Engineering Society	IES
Industrial Fasteners Institute	IFI
Institute of Electrical & Electronics Engineers	IEEE
Instrument Society of America	ISA
Insulated Cable Engineers Association	ICEA
National Association of Corrosion Engineers	NACE
National Board of Fire Underwriters	NBFU
National Electrical Code	NEC
National Electrical Contractors Association	NECA
National Electrical Manufacturers Association	NEMA
National Electrical Testing Association	NETA
National Electrical Safety Code	NESC
National Fire Protection Association	NFPA
Occupational Safety and Health Administration	OSHA
Steel Structures Painting Council	SSPC
Underwriters Laboratories	UL

Additionally, the system must also meet the applicable state, county, and city codes and regulations.

6.6.3 ENVIRONMENTAL CONSIDERATIONS (2021)

Environmental considerations include the impact of the environment onto the electrification system and the impact of the electrification system on the environment. The adverse impacts of both factors should be limited as much as is economically possible.

6.6.3.1 Climatic Conditions

The traction electrification system should be designed taking into account the climatic conditions in the project locale. The

substation, paralleling station and switching station sites should be located away from flood zones. Alternately, if these have to be located in flood zones, these facilities should be located above the 'Design Flood Level – the height flood waters are expected to rise to in a future storm at that site'. The design flood level for each site is determined by hydraulic and hydrological studies of each area. The climatic conditions should include the maximum and minimum values for the following parameters:

- Maximum and minimum ambient temperature (°F)
- Maximum ice thickness (inches)
- 24-hour rainfall (inches)
- Design flood level
- Maximum and minimum relative humidity (%)
- Maximum wind speed (mph)
- Altitude above sea level (feet)
- Existence of any corrosive atmosphere, such as salt spray or industrial air pollution

The climatic factors at the project altitude should be used as the design guidelines. The climatic factors should be given for the system operating conditions and structural design, and should be derived from publicly-available data recorded in the project locale.

6.6.3.2 Environmental Impact Statement

If federally funded, the electrification project is likely to require an Environmental Impact Statement (EIS). The factors which will have to be addressed include protection of natural resources during construction and operation, soil erosion and sedimentation, air quality improvement, wetlands, wildlife, noise and vibration, and aesthetic impact. Adverse effects on the environment should be limited as much as is economically possible. In order to avoid regulatory delays, it is recommended that the EIS be prepared as soon as possible after the project commencement. All possible candidate sites for substations, paralleling stations, and switching stations should be included in the environmental impact study of the project.

6.6.4 SERVICE CONDITIONS (2009)R(2021)

It is recommended that the following service conditions be identified in the equipment specifications:

- Indoor or outdoor installation requirement
- Seismic levels or vibrations from passing trains
- Short circuit duty at utility substations and line tapping points
- Short circuit duty at the traction transformer secondary windings
- Rolling stock harmonic frequency spectrum magnitude and power factor

6.6.5 EQUIPMENT DESIGN (2021)

Traction power equipment is generally located in unmanned substations, paralleling stations, and switching stations, and therefore, the equipment should be simple and reliable. The equipment should be designed considering long term remote operation and ease of access for testing and maintenance.

6.6.5.1 Basic Impulse Insulation Level

An insulation coordination study is recommended to be performed for all voltage levels in the traction power substations, so that suitable Basic Insulation Level (BIL) and appropriate surge arresters can be selected. The primary voltage equipment BIL, applicable to HV circuit breakers, HV disconnect switches and transformer primary windings, must be fully coordinated with the utility system BIL. The low (secondary) voltage system BIL, applicable to transformer secondary windings and switchgear, is recommended to be as shown below:

Electrification Voltage (kV)	Minimum Equipment BIL (kV)
12.5	150
25	250 / 200*
50	450

*200 kV BIL may be considered for indoor switchgear if required.

The surge arresters and surge protecting devices should be applied in accordance with IEEE C62 series of standards.

6.6.5.2 Tests

Comprehensive tests should be specified for all substation equipment including design, production and installation verification tests in accordance with the relevant IEEE, ANSI and NEMA standards. When large numbers of equipment are being purchased under the same contract, the buyer should reserve the right to repeat the basic acceptance tests on a random sample of the batch in order to maintain quality control.

6.6.5.3 Spare Parts, Special Tools and Test Equipment

All traction power supply equipment is recommended to be ordered with a full complement of spare parts, special tools and test equipment in sufficient quantity to last two years after equipment acceptance. The procurement documents should request guaranteed cost of additional equipment for an order executed within the two years.

6.6.5.4 Documentation

Each manufacturer should be required by specification to furnish a comprehensive set of documentation with the delivered equipment. This documentation is recommended to include product data, fully dimensioned drawings including weights and erection details, preventive maintenance, corrective maintenance and heavy repair manuals, test procedures, and test results.

6.6.6 HIGH (PRIMARY) VOLTAGE CIRCUIT BREAKERS AND DISCONNECT SWITCHES (2009)R(2021)

Selection of high (primary) voltage circuit breakers, disconnect switches and protective equipment is governed by the circuit voltage level and short circuit fault level existing at the particular electrical power utility supply. The high voltage supply arrangement and protection should be designed in accordance with the power utility practices and should be reviewed by the power utility. The high voltage circuit breakers and disconnect switches should be installed in accordance with IEEE C37 series of standards.

6.6.7 TRACTION POWER TRANSFORMERS (2021)

Consideration should be given to specifying traction power transformers for a particular project with the same characteristics to standardize design and maintenance, and permit equipment interchangeability. The traction power transformers should be installed in accordance with IEEE C57 series of standards.

6.6.7.1 Continuous and Overload Current Ratings

Substation transformers should be rated on the basis of the Load Flow Study results. Each transformer must be rated to supply continuously its own load under normal operating conditions, together with the additional load of the adjacent electrical section under a transformer or substation outage. Because of the traction load fluctuation, it is recommended that the transformers should be specified to supply the rated power continuously with superimposed overload cycle equal to 150% of continuous rating for 2 hours and 300% of continuous rating for 5 minutes without significant reduction of service life expectancy.

It is recommended that transformer rating includes spare capacity for future increases in train sizes or number of trains in operation.

6.6.7.2 Temperature Rise

The IEEE standard recommends that the transformer winding temperature rise above ambient temperature, based on its continuous rating, should not be permitted to exceed 65°C using resistance measurements. However, due to the fluctuating nature of the traction current and the presence of harmonics, the designer may use a lower value. The winding hottest-spot temperature rise is recommended to be less than 80°C.

6.6.7.3 Harmonics

Propulsion equipment on rolling stock will generate harmonic currents. Harmonic currents increase the total RMS current loading of the traction power substation and power utility equipment, and therefore, produce additional heating. Coordination with the vehicle design team is recommended to determine the level of harmonic currents. It is recommended that the transformer specifications include the projected RMS current values of all harmonics expressed as a percentage of fundamental frequency. As a minimum, harmonics from the third through the twenty-first harmonic should be included.

6.6.7.4 Impedance

The selected value of transformer impedance must be low enough to avoid excessive voltage drop in order to obtain long substation feeding distances. The impedance should not be too low, however, as this would affect the economy of transformer and low voltage switchgear design due to higher short circuit current. Judgment based on engineering and economic factors is required to obtain the optimum value.

6.6.7.5 Core and Windings

The fluctuating load currents and relatively high incidence of heavy fault currents produce pulsating forces and mechanical stresses in the transformer windings. These forces and stresses may cause axial and radial movement of the coils and eventual transformer failure. It is recommended that the specifications include the requirement for augmented mechanical strength of the transformer core and include an internal bracing system for windings. Winding and tap connections should be located to minimize their movement and damage.

6.6.7.6 Voltage Ratios and Tap Changers

It is recommended that the transformer no-load voltage ratio at a normal tap position be for "nominal voltage plus 5%." For example, for a 25 kV system the transformer secondary voltage is recommended to be set at 26.25 kV. This allows for utility voltage variation of +5% without exceeding the normal upper voltage of 27.5 kV. It is recommended that four (4) no-load taps in 2.5% increments, two (2) below and two (2) above the normal tap be provided to permit such adjustments.

In locations where the utility voltage varies in wide ranges, application of transformer load tap changer may be considered. However, since load tap changers increase the transformer maintenance and initial costs, their operation should be limited only to adjust for utility voltage variation and their operation should be precluded due to voltage drop caused by passing trains.

6.6.7.7 Oil Preservation and Pressurization System

It is recommended that each transformer be equipped with oil expansion tanks and an inert gas pressure system along with appropriate gauges, alarms and safety valves. Removable radiators are recommended to facilitate maintenance. The large volume (several hundred gallons) of cooling oil in the transformer tank and radiators creates a large heat sink that can absorb significant overloads under cyclic loading without any adverse effects on the transformer. The transformers should be installed with oil containment provisions required to comply with the IEEE/ANSI standards requirements and to minimize environmental damage in the event of a leak in the tank or radiators.

6.6.7.8 Noise Level

The specifications should include maximum exterior noise levels, in accordance with IEEE/ANSI Standards, if the transformer is to be located in a populated area.

6.6.7.9 Acceptance Tests

Short circuit tests should be considered an essential part of the acceptance procedure, due to the operating environment of the transformer. Tests should be run for each primary voltage type and each rating of the transformers.

6.6.8 MEDIUM (SECONDARY) VOLTAGE SWITCHGEAR (2009)R(2021)

The OCS is susceptible to frequent short circuit faults and, therefore, switchgear with vacuum or sulfur hexafluoride (SF_6) circuit breakers is recommended. The circuit breakers should be capable of several hundred operations at short circuit current levels and several thousand operations at rated current levels. The medium voltage switchgear should be applied in accordance with IEEE C37 series of standards.

6.6.8.1 Switchgear Type

Whenever voltage rating permits, metal-clad switchgear assemblies with horizontal draw-out circuit breakers are recommended. The switchgear should be located in metal or brick housings and installed in dead-front, floor-mounted, free-standing cubicles. Indoor, fixed, metal-enclosed switchgear or outdoor circuit breakers are recommended alternatives to the metal-clad, draw-out circuit breaker type switchgear.

6.6.8.2 Ratings

Switchgear and circuit breakers are recommended to be rated on a symmetrical current basis as recommended by the IEEE/ANSI C37 series of standards. The continuous and overload ratings of feeder switchgear should be compatible with the overhead conductor ampacity and the traction transformer rating. The incoming and bus-tie switchgear are recommended to be rated at a higher continuous current rating than the feeder switchgear.

The switchgear must be able to carry the short circuit current for sufficient time to enable the protective relaying to operate. Once the switchgear is required to open, current interruption should be fast without restrike due to transient voltage recovery.

6.6.9 SYSTEM PROTECTION (2021)

6.6.9.1 Transformer Protection

Each traction power transformer is recommended to be equipped with phase and ground fault overcurrent relays and differential relays. Two stage winding and oil temperature relays should be provided, which should be designed to provide an alarm at lower excess temperature level and to open the circuit breakers at higher excess temperature. A two-stage sudden pressure relay (Buchholz relay) for internal transformer faults should initiate an alarm for gas accumulation and trip out the transformer with an oil surge. A two stage oil level relay is recommended to be provided with transformers with conservator tanks. First stage will provide an alarm; second stage will trip and lockout the primary and secondary side transformer circuit breakers.

6.6.9.2 Catenary Protection

The catenary system can experience high peak load currents and low fault currents which can be comparable in magnitude. This precludes the use of overcurrent type protection, as overcurrent relaying cannot distinguish between the high load and low fault currents.

The most feasible solution for catenary protection is the use of distance relaying. It is comparatively simple to apply, is of high speed class, and provides primary and back up protection in a single scheme. The distance relay measures impedance along the protected line and is arranged to operate for faults between the relay location and a selected point. The relay reach is usually divided into three protection zones, thus enabling time discrimination for faults in different line sections.

Faults occurring in the Zone 1 are recommended to be cleared with no intentional time delay. Zones 2 and 3 should have adjustable time delays and train start detection feature using di/dt, dv/dt, and dcp/dt to trigger conditions to prevent the distance relay operation under train accelerating current. Further, it is recommended that the relay be equipped with circular and polygonal tripping characteristic with independently adjustable line resistance, line reactance, and "load blinding" settings to prevent the relay operation on train load.

A high proportion of catenary faults are of transient nature and will clear once the circuit breaker is opened and the air in the fault location is de-ionized. Depending on the railroad operating practices, use of an auto-reclosing device can be considered. Such a relay will reclose the circuit breaker after an interval of 3 to 15 seconds, if not manually overridden. In the case of persistent faults, the circuit breaker will latch out on the second or third opening.

In addition to distance relaying, consideration should also be given to thermal overload protection which prevents the system conductors from overheating and possible annealing. In order to accelerate the fault clearance, and in special circumstances, where sufficiently high short circuit currents are not available to clear remote faults, transfer trip of remote circuit breakers using pilot wire or fiber optic communication can be considered.

Catenary system protection must be immune to system harmonics and autotransformer inrush currents, and must ensure full discrimination of protective devices. The protection must also provide a complete back up in the case of breaker or relay failure and be inoperative under inrush of magnetizing current to autotransformers and rolling stock on-board transformers.

6.6.9.3 Overvoltage Protection

It is recommended to provide comprehensive overvoltage to protect the traction power supply system and its components from overvoltages caused by lightning strikes or switching surges. The protective equipment should include appropriately rated surge arresters and transient voltage surge suppressors. The grounding connection of the surge arresters should be as short as possible and without unnecessary bends in the grounding wire. Recommended standards for application of surge protection include Underwriters Laboratories, UL 96A, National Fire Protection Agency's NFPA 780, and Lightning Protection Institute's LPI 175.

6.6.10 SPECIAL EQUIPMENT (2021)

6.6.10.1 Load Balancing Equipment

In the event that at a particular location the power utility short circuit level is low and the traction load is high, utility system voltage and current unbalance may exceed the unbalance limit. Although this is a relatively rare phenomenon, the high unbalance can be corrected by using static or dynamic load balancing equipment.

6.6.10.2 Power Factor Correction and Harmonic Frequency Filtering

Design of equipment such as power factor correction capacitors and harmonic frequency filters should take into consideration the presence of voltages and currents at harmonic frequencies. It is recommended that the traction power design should take into account harmonics caused by traction loads as well as harmonics that may be already present on the utility system. With increased frequency of harmonics the capacitor impedance decreases and the capacitors may become overloaded and overheated. Since the need for harmonic filters is determined in the utility studies as part of the design phase, it is recommended that ground space for special equipment is allocated at traction power substation sites at the conceptual design stage.

6.6.11 SIGNAL POWER GENERATING SYSTEM (2021)

The power supply for signaling, which often uses 100 Hz or 91-2/3 Hz power, can be derived from the local power utility or from the traction power supply. The conversion equipment can be located at the traction power substations. Trackside signal power supply generation equipment usually include a motor/generator set or a solid state converter and associated transformers, control and protective equipment. Use of utility power supply is recommended for generation of signal power supply, since the traction power supply voltage is subject to wide fluctuations and is likely to contain harmonics.

The system specifications should include limits on frequency and voltage variations. In order to maintain continuous power

supply, back-up generators or converters should be provided for a trackside system with automatic power transfer equipment enabling transfer from main to back up supply during emergencies. For direct utility supply, it is recommended that dual supply lines should be installed with automatic transfer equipment. Depending on the signaling system, the restoration of signal power is required to be achieved in a specified time to avoid interfering with normal train operation.

6.6.12 SUPERVISORY CONTROL AND DATA ACQUISITION SYSTEM (SCADA) (2021)

The use of a computer-based SCADA system is recommended for monitoring and control of the unmanned traction power supply, signaling power supply and system sectioning facilities. As a minimum the system should incorporate the following features:

- Remote control of all circuit breakers, motor-operated disconnect switches and electrical lockout relays
- Status indication of all circuit breakers, disconnect switches and grounding switches
- Status indication of protective relaying, ac auxiliary power equipment and dc auxiliary power equipment including the station battery and battery charger
- Status of communication system
- Enable/disable automatic reclosing of circuit breakers
- Metering of ac and dc voltages, currents, real power (kW), reactive power (kVAr), and energy consumption (kWh)
- Maximum demand
- Recording of maintenance clearance permits and maintenance status
- Work permit, power removal and out of service equipment tagging
- Catenary power removal coordination with railroad operations and track blocking
- Annunciation of circuit breaker tripping, all alarms, and low substation voltages
- Annunciation of facility intrusion and smoke/fire alarms
- Sequence of events recording
- Voice communication

Depending on the system size, it is recommended that the SCADA system be equipped with one or more color visual display units at the control center. It is also recommended that the selection and de-selection of equipment and control command transmittal be performed from the computer keyboards. In order to facilitate SCADA system maintenance, software changes, and to avoid disruption of service due to failures, duplication of the SCADA system is recommended at each railroad control center.

SECTION 6.7 UTILITY METERING

6.7.1 TYPICAL RATE STRUCTURE (2021)

Every power utility company has a different rate structure with the same or similar components. A typical rate structure for

provision of electrical power to the railroad may consist of the following:

- Energy charge - includes charge for energy consumed over a billing period of time. Although not common, the energy charge may use ratchets.
- Fuel cost adjustment - includes adjustment for fuel cost variation.
- Demand charge - covers the utility generation and transmission costs. The demand charge may or may not use ratchets.
- Dedicated utility facility cost - covers major connection costs.
- Miscellaneous charges - may include connection charges, and penalties for low power factor and excessive phase unbalance.
- Discounts - may include high voltage service and off-peak usage discounts.

6.7.2 LOCATION OF METERING EQUIPMENT (2021)

The metering equipment can be located on the substation high (primary) voltage side or at the traction power transformer secondary as agreed with the utility. The primary voltage metering requires more expensive HV potential and current transformers, while the low (secondary) voltage metering is more complex as it must compensate for transformer losses. Overall, the secondary voltage metering system is less expensive and therefore is recommended whenever permitted by the utilities.

6.7.3 BILLING CONCEPTS (2009)R(2021)

Each power utility may have a different rate structure and the tariff applied to a railroad electrification supply has to be negotiated. It is recommended that the billing concepts presented in this section be included in such negotiations.

6.7.3.1 Conjunctive Billing

Coincidental or conjunctive billing is applicable when several substations are supplied by the same utility. Due to the fact that the train load moves along the alignment, peak demands on individual substations are unlikely to occur simultaneously. Therefore, coincident power demand measured at several substations during the maximum demand period is likely to be lower than the sum of maximum demands as measured individually at each substation. Considerable billing savings can be realized by totaling the power demands of several substations at coincidental time interval.

6.7.3.2 Time-of-Day and Time-of-Year Pricing

These pricing concepts are designed to charge a higher rate during peak-load periods and lower rates at other times.

6.7.4 RATE STRUCTURE NEGOTIATION (2009)R(2021)

It is recommended that the electrification system owner begin early discussions with the power utilities to negotiate the most advantageous electrical rate structure and identify any possible connection costs. It is recommended that during the negotiations the system owner is supported by technical staff as well as by an experienced rate structure attorney to achieve most advantageous tariff for the expected load.

SECTION 6.8 CONSTRUCTION

6.8.1 QUALITY ASSURANCE/QUALITY CONTROL (2021)

The Quality Assurance/Quality Control (QA/QC) program established at the commencement of the design stage should be maintained. During manufacturing and construction stages of the project it is recommended to monitor the quality of work by observing manufacture, and inspecting construction. Design, production and routine tests required by applicable standards must be performed and witnessed by the railroad engineers. Installation of equipment should be regularly inspected to assure quality control, especially for the hidden works like cables, foundations, and grounding grids.

6.8.2 INSTALLATION VERIFICATION TESTING (2021)

Field tests should be performed to verify that the system has been correctly installed and that there are no equipment omissions or incompatibilities. Verification that all equipment is installed according to the design and is in operable condition should be performed prior to conducting the field tests, including:

- Visual inspection of equipment.
- Calibration and adjustments of protective relays and instruments.
- Connection check of feeders and disconnect switches.
- High potential feeder insulation check.

The following tests are recommended:

- Substation grounding resistance test
- Substation equipment, power cables, and control wiring dielectric tests
- Substation equipment functional and operational tests including tests of safety interlocks
- Substation Infrared temperature measurement of all busbar connections, cable splices
- Substation relay coordination and calibration tests including short circuit tests:
  - Line-to-rail short circuit, local and remote, bolted and high-resistance
  - Line-to-ground short circuit, local and remote, bolted and high-resistance
- Substation audible sound-level test while two trains are starting at full acceleration
- System Safety Certification should be considered

6.8.3 SYSTEM-WIDE INTEGRATION TESTING (2021)

System-wide integration tests should be performed to verify that the traction power supply, the traction power distribution, and the traction power return systems have been correctly integrated with the rolling stock, signal system, and communications system, and that there are no system incompatibilities.

The following tests are recommended:

- Train Operation Tests. The test should be performed with all substations in service and with one substation out-of-service. As a minimum, following data should be measured and recorded the during the tests:
  - Train voltage
  - Train current

- All feeder circuit breaker currents at three adjacent substations

- Supervisory Control and Data Acquisition System. Following installation of the SCADA system and communications system, interface tests should be conducted to verify the following:

  - Proper operation of all SCADA equipment, locally and from the control center.

  - Proper data communications from the control center to and from each PLC.

6.8.4 PRE-REVENUE OPERATION TESTING (2021)

Following satisfactory completion of all individual equipment tests, system installation verification testing, and system-wide integration testing, a system pre-revenue operation test should be conducted.

During the test, rolling stock consists should be operated at minimum headways and the following functions monitored and recorded:

- All substation equipment parameters including harmonic level and voltage unbalance at the adjacent substations

- Pantograph voltage on a few representative trains

- Return of unused energy from regenerative braking to utility grid, if agreed by the utility, should be verified

- Above tests should be repeated with one substation out of service

- All SCADA functions for satisfactory operation, including:

  - All control functions from the Control Console and remotely located PC

  - All monitoring functions

  - All measuring functions