II Design Criteria for Electrical Facilities Connected to the PJM 765 kV, 500 kV, 345 kV, 230 kV, 138 kV, 115 kV, & 69 kV Transmission Systems

These design criteria have been established to assure acceptable reliability of the Bulk transmission system facilities. These set forth the service conditions, and establish insulation levels for overhead and underground lines and substations, and short circuit levels for substations. Specific component requirements are listed in their own sections (in addition to NESC the IEC 61936 could be a good reference).

1.0 Design Criteria

Environmental (Atmospheric, Geologic, etc.) and Structural requirements apply to 69 kV, 115kV, 138kV, 230 kV, 345 kV, and 500 kV, 765 kV, conductors, structures, and equipment; both for Lines and Substations. Electrical requirements are Voltage Specific.

2.0 Environmental Overhead Lines and Substations

Ambient Temperature	-30 (-40)° C to +40° C (-40° C minimum may be required for areas where low temperature weather presents)
Wind loading Substations (no ice)	per ASCE 7-10, Figure 6-1 depending on location [typically 90 to 110 mph]
Wind loading Lines (no ice) 138 kV or less Wind loading Lines (no ice) greater than 138 kV	per NESC Extreme Wind 25 psf or NESC Extreme Wind (whichever is greater)
Ice load 765 kV or less lines (no wind)	TBD (AEP, ComEd)
Ice load 500 kV, 345 kV, 230 kV lines (no wind)	38 mm radial ice
Ice load 138 kV or less lines (no wind)	Per TO's recommendation
Ice load substations (no wind)	25 mm radial ice
Wind coincident with 13 mm radial ice	64 km/h (40 mph)
Seismic Substations	per ASCE 7-10 0.2 s and 1.0 s Spectral Response Acceleration (5% of Critical Damping), Site Class B.(Figure 9.4.1.1 (a) & (b)) Equipment qualification per IEEE 693-2005. [Typically 0.2 g some as high as 0.4 g]
Line design	NESC Heavy Loading (latest edition)
Flood Plain	Structure ground line above 100 yr flood where possible

3.0 Substations General

AC Station Service	Two independent sources with automatic throwover (emergency generators may be required where black start capability is required)
DC supply	Separate batteries for primary and back up protection are desired, or required. 8 hr capacity required for all control batteries, and they should be fed with 2 independently supplied chargers.
Ground grid resistance	1 ohm or less

4.0 765 kV Substations Electrical

Line Terminal and Equipment Continuous Current	4000 A
3 second current (short circuit)	50 kA X/R = 50 63 kA X/R =17
Operating Voltage (Transformer must accommodate the voltage range expected at the point of application)	800 kV
RIV level at 350 kV line to ground	No longer use RIV as a design point. Partial discharge testing accounts for RIV
Lightning Impulse Withstand Voltage w/o line entrance arresters	2,050 kV
Lightning Impulse Withstand Voltage with line entrance arresters	2,255 kV
Switching Impulse withstand level (20)	1,700 kV
Typical Surge Arrester	588 kV
Circuit Breaker line closing switching surge factor	2.2 Depending on the switching surge studies
System Grounding	Effectively Grounded Neutral (always)
Lightning trip out Performance (station)	N/A, not a station design criteria
Fault performance (circuit failure, including momentary) all other causes	N/A, not a station design criteria

4.1 765 kV Line Electrical

RIV level at 464 kV line to ground	Pending updates.
Switching Impulse withstand level (3σ)	1,050 kV
250 x 2,500 µs minimum critical flashover	1,400 kV
1.2 x 50 µs minimum critical flashover (lightning) CIFO	2,530 kV
Lightning Trip out Performance (line)	Target - 1/100 mi (160 km) per year. Use lightning density from NLDN data.
Line trip out performance from all other causes	N/A, not a design criteria

Table 1 – Transmission Line Design Parameters

Parameter	765 kV
Ambient Temperature Range	If this range is used for line rating, then the values are acceptable. If used for another purpose, please provide context (-30° C to +40° C (from -40° C N & W of Blue Mountain)
Minimum Extreme Wind Loading	Based on 100 yr Return Period or Mean Recurrence Interval
Heavy Ice Load (No Wind)	1.25" unless in heavy icing region, then by study.
Code Requirements	NESC Grade "B", Heavy Loading District
Flood Plain	The line shall meet the applicable Local, State, and Federal regulations.
Damper Requirements (Tensions at 0° F)	Design by engineering study
Galloping Assumptions	Use RUS methodology
Galloping Mitigation	10% overlap single loop, no overlap double loop.
Anti-galloping devices	Acceptable
Spacers	Controlled by bundle size.
Provisions for Live Line Maintenance	As required by the TO.
Access Requirements	Construction and maintenance access is required to each structure.

Approved conductor sizes for NEW Construction	By design.
Approved static and OPGW wire sizes for NEW Construction	By design.
Right-of-way width (Target values)	200 ft minimum
Max. Number of circuits per structure	1 unless specifically approved by TO
Min. design ground clearance at Max. Sag	NESC minimum requirements PLUS an additional 2 ft
Conductor to structure steel clearance (min.)	162 in
Insulation - Leakage distance (min.)	330 in (ceramic or glass)
Insulation - 60 Hz WET (min)	1,100 vkV
Insulation - Switching Surge	2.0
Insulation - Critical Impulse Flashover (min.)	2,530 kV
Maximum Structure Ground Resistance	Target 20 Ω
Step & Touch Potential Issues	Provide a structure grounding system that meets the step and touch requirements of the TO.
Minimum Number of Static Wires Required	2 per structure
Isokeraunic Level	Use NLDN data for lightning density
Maximum Shielding Angle	15°
Target Lightning Outage Performance (new construction)	Target 1 per 100 circuit-miles/yr. by design
EMF Limits	As Required by TO and State Regulatory Agencies
Radio Interference at edge of right-of-way (under fair weather conditions)	Please provide additional information as to the use of this parameter.
Audible Noise	Per applicable state and local laws for noise at edge of right-of-way

5.0 500kV Substations Electrical

Line Terminal and Equipment Continuous Current	3,000 A
3 second current (short circuit)	40 kA (X/R = 25) DC time constant 60 ms {higher duties required at some locations usually < 63 kA}
Operating Voltage (Transformer must accommodate the voltage range expected at the point of application)	500 kV to 550 kV 500 kV nominal (typical "normal" voltages range from 515 kV to 550 kV)
RIV level at 350 kV line to ground	300 uV at1 MHz
Lightning Impulse Withstand Voltage w/o line entrance arresters	1,800 kV
Lightning Impulse Withstand Voltage **with** line entrance arresters	1,550 kV
Switching Impulse withstand level (20)	1,050 kV
Typical Surge Arrester	318 kV MCOV Station Class (396 kV duty cycle)
Circuit Breaker line closing switching surge factor	2.2 (i.e. closing resistors required & no restrikes, or line end arresters used to clamp switching overvoltages.)
System Grounding	Effectively Grounded Neutral (always)
Lightning trip out Performance (station)	1/100 yr Keraunic level =40
Fault performance (non-lighting)	1/40 yr/breaker position

5.1 500kV Overhead Line Electrical

RIV level at 350 kV line to ground	300 uV at1 MHz
Switching Impulse withstand level (30)	990 kV
250 x 2,500 µs minimum critical flashover	1,200 kV
1.2 x 50 µs minimum critical flashover (lightning)	2,145 kV
Lightning Trip out Performance (line)	1/100 mi (160 km) per yr Keraunic level=40
Line trip out performance from all other causes	1/100 mi (160 km) per yr

6.0 **345kV Substations Electrical**

Line Terminal and Equipment Continuous Current	2,000 A (or as required at the connecting point)
3 second current (short circuit)	40 kA (X/R=25) DC time constant 60 ms {higher duties required at some locations usually < 63 kA}
Operating Voltage (Transformer must accommodate the voltage range expected at the point of application)	325 kV to 362 kV 345 kV nominal (typical "normal" voltages range from 345 kV to 362 kV)
RIV level at 230 kV line to ground	300 uV at 1 MHz
Lightning Impulse Withstand Voltage w/o line entrance arresters	1,300 kV
Lightning Impulse Withstand Voltage With line entrance arresters	1,050 kV
Switching Impulse withstand level (20)	750 kV
Typical Surge Arrester	209 kV MCOV Station Class (258 kV duty cycle)
Circuit Breaker line closing switching surge factor	2.2 (i.e. closing resistors required & no restrikes, or line end arresters used to clamp switching overvoltages.)
System Grounding	Effectively Grounded Neutral (always)
Lightning trip out Performance (station)	1/100 yr Keraunic level =40
Fault performance(non-lighting)	1/40 yr/breaker position

6.1 345kV Overhead Line Electrical

RIV level at 230 kV line to ground	300 uV at 1 MHz
Switching Impulse withstand level (30)	700 kV
250 x 2,500 μs minimum critical flashover	840 kV
1.2 x 50 μs (Lightning Impulse) minimum CFO	1,440 kV
Lightning Trip out Performance (line)	1/100 mi (160 km) per yr Keraunic level=40
Line trip out performance from all other causes	1/100 mi (160 km) per yr

7.0 **230kV Substation Electrical**

Line Terminal & Equipment Continuous Current	To match connecting point or 2,000 A
3 second short circuit current	40 kA (X/R=20) DC time constant 48 ms {higher duties required at some locations usually < 63 kA}
Operating Voltage (Transformer must accommodate this range)	220 kV to 242 kV 230 kV nominal
Lightning Impulse Withstand Voltage	900 kV BIL
Typical Surge Arrester	144 kV MCOV Station Class (180 kV Duty Cycle)
Lightning trip out Performance (station)	1/100 yr Keraunic level =40
Fault performance (non-lighting)	1/40 yr/breaker position
System Grounding	Effectively Grounded Neutral (always)

7.1 230kV Overhead Line Electrical

Lightning Trip out Performance (line)	2/100 mi (160 km) per yr Keraunic level=40
Line trip out performance from all other causes	2/100 mi (160 km) per yr
1.2 x 50 µs (Lightning Impulse) minimum CFO	1,105 kV

8.0 **138 kV Substation Electrical**

Line Terminal & Equipment Continuous Current	To match connecting point or 2,000 A
3 second short circuit current	40 kA (X/R=20) DC time constant 48 ms {higher duties required at some locations usually < 63 kA}
Operating Voltage (Transformer must accommodate this range)	131 kV to 145 kV 138 kV nominal (*)
Lightning Impulse Withstand Voltage	650 kV BIL
Typical Surge Arrester	98 kV MCOV Station Class (120 kV Duty Cycle)
Lightning trip out Performance (station)	1/100 yr Keraunic level =40
Fault performance (non-lighting)	1/40 yr/breaker position
System Grounding	Effectively Grounded Neutral (always)

8.1 138 kV Overhead Line Electrical

Lightning Trip out Performance (line)	2/100 mi (160 km) per yr Keraunic level=40
Line trip out performance from all other causes	2/100 mi (160 km) per yr
1.2 x 50 µs (Lightning Impulse) minimum CFO	860 kV

9.0 **115 kV Substation Electrical**

Line Terminal & Equipment Continuous Current	To match connecting point or 2,000 A
3 second short circuit current	40 kA (X/R=20) DC time constant 48 ms {higher duties required at some locations usually < 63 kA}
Operating Voltage (Transformer must accommodate this range)	109 kV to 121 kV 115 kV nominal
Lightning Impulse Withstand Voltage	550 kV BIL
Typical Surge Arrester	84kV MCOV Station Class (180 kV Duty Cycle)
Lightning trip out Performance (station)	1/100 yr Keraunic level =40
Fault performance (non-lighting)	1/40 yr/breaker position
System Grounding	Effectively Grounded Neutral (always)

9.1 115 kV Overhead Line Electrical

Lightning Trip out Performance (line)	2/100 mi (160 km) per yr Keraunic level=40
Line trip out performance from all other causes	2/100 mi (160 km) per yr
1.2 x 50 µs (Lightning Impulse) minimum CFO	670 kV

10.0 **69 kV Substation Electrical**

Line Terminal & Equipment Continuous Current	To match connecting point or 2,000 A
3 second short circuit current	40 kA (X/R=20) DC time constant 48 ms {higher duties required at some locations usually < 63 kA}
Operating Voltage (Transformer must accommodate this range)	66 kV to 73 kV 69 kV nominal
Lightning Impulse Withstand Voltage	350 kV BIL
Typical Surge Arrester	57 kV MCOV Station Class (66 -72 kV Duty Cycle)
Lightning trip out Performance (station)	1/100 yr Keraunic level =40 (recommended)
Fault performance (non-lighting)	1/40 yr/breaker position (recommended)
System Grounding	Effectively Grounded Neutral (always)

10.1 69 kV Overhead Line Electrical

Lightning Trip out Performance (line)	3/100 mi (160 km) per yr Keraunic level=40
Line trip out performance from all other causes	3/100 mi (160 km) per yr
1.2 x 50 μs (Lightning Impulse) minimum CFO	~~670~~ kV

III. Substation Bus Configurations & Substation Design Recommendations

1.0 Introduction

Pre-existing conditions, electrical arrangements or the criticality of the existing facility may limit this flexibility, but the interconnection arrangement must provide a high degree of reliability, operability and maintainability for the Transmission System. For these reasons, ring-bus or breaker-and-a-half switchyard schemes are preferred for transmission switchyards. Three terminal lines are generally not considered acceptable. For generation interconnections, a line tap is not considered acceptable. There may also be instances when it is not considered prudent or practical to further extend an existing ring bus. Reasons for changing from a ring bus to a breaker-and-a-half arrangement might include the criticality or size of the load or generation to be interconnected, or the number of bus positions in existence or planned for the future. The larger the ring bus the greater the probability becomes during normal operations, multi-system events and maintenance that the substation could become fragmented into multiple pieces thereby losing its level of reliability.

The level of reliability for interconnected generation should be consistent with the generation's anticipated availability and frequency of operation. Multiple generators bussed onto a single line, for example may minimize transmission interconnection cost, but it could be at the risk of severe economic lost-opportunity consequences for a single contingency failure.

In addition to arrangement, design criteria have been established to assure acceptable reliability of the bulk electric system facilities. These set forth the service conditions, and establish insulation levels and short circuit levels for substations. Many of these parameters were taken from Keystone, Conemaugh, Susquehanna Eastern, Lower Delaware Valley (LDV), and/or EHV projects. Specific component requirements are listed in their own sections (in addition to NESC the proposed IEC 61936 could be a good reference). Environmental (atmospheric, geologic, etc.) and structural requirements apply to bulk electric system conductors, structures, and equipment. Electrical requirements are voltage specific.

2.0 Environmental

Environmental values are typical. Contact Interconnected Transmission Owner for area specific parameters.

Parameter	Basis
Ambient Temperature	-22 °F to +104 °F (-40 minimum required N and W of Blue Mountain, PA)
Extreme Wind Loading outdoor substation equipment (no ice)	per ASCE 7-10, *Figure 6-1 depending on location [typically 90 to 110 mph]*
Heavy Ice Loading outdoor substation equipment (no wind)	1 in radial ice
Coincident Wind & Ice Loading	NESC B & C (40 mph)
Seismic Substations	per ASCE 7-98 0.2 s and 1.0 s Spectral Response

	Acceleration (5% of Critical Damping), Site Class B.(Figure 9.4.1.1 (a) & (b)) Equipment qualification per IEEE 693-97. [Typically 0.2 g some as high as 0.4 g]
Flood Plain	Structure ground line above 100 yr. flood where possible
AC Station Service	Two independent sources with automatic throwover (Emergency generators may be required where black start capability is required per TO's restoration criteria)
DC supply	Separate batteries for primary and back up protection are desired. Minimum 8 hr capacity is required for all control batteries, and they should be fed with 2 independently supplied chargers
Ground grid resistance	1 ohm or less

3.0 Electrical

Electrical values are typical. Contact Interconnected Transmission Owner for area specific parameters. Additional data for 765 kV and 69 kV Ref. Chapter II.

Parameter	500 kV	345 kV	230 kV	138 kV	115 kV
Line Terminal and Equipment Continuous Current	3000 A	2000 A (or as required at the connecting point)	To match connecting point or 2000 A	To match connecting point or 2000 A	To match connecting point or 2000 A
3 second current (short circuit)	40 kA (X/R 25) DC time constant 60 ms	40 kA (X/R 25) DC time constant 60 ms	40 kA (X/R = 20) DC time constant 48 ms (higher duties required at some locations usually <63 kA)	40 kA (X/R = 20) DC time constant 48 ms (higher duties required at some locations usually <63 kA)	40 kA (X/R = 20) DC time constant 48 ms (higher duties required at some locations usually <63 kA)
Operating Voltage (Transformer must accommodate the voltage range expected at the point of application)	450 kV to 550 kV 500 kV nominal (typical “normal” voltages range from 515 kV to 550 kV)	325 kV to 362 kV 345 kV nominal (typical “normal” voltages range from 345 kV to 362 kV)	220 kV to 242 kV 230 kV nominal	132 kV to 145 KV 138 kV nominal	109 kV to 121 kV 115 kV nominal
RIV level	300 uV @ 1 MHz (350 kV)	300 uV at 1 MHz 300 uV at 1 MHz (230 kV)	N/A	N/A	N/A
Lightning Impulse Withstand Voltage w/o line entrance arresters	1800 kV	1300 kV	900 kV BIL	650 KV BIL	550 kV BIL
Lightning Impulse Withstand Voltage with line entrance arresters	1550 kV	1050 kV			
Switching Impulse withstand level (2σ)	1050 kV	750 kV	N/A	N/A	N/A
Typical Surge Arrester	318 kV MCOV Station Class (396 kV duty cycle)	209 kV MCOV Station Class (258 kV duty cycle)	144 kV MCOV Station Class (180 kv Duty Cycle)	98 kV MCOV Station Class(120 kV Duty Cycle)	84kV MCOV Station Class (180 kV Duty Cycle)

Parameter	500 kV	345 kV	230 kV	138 kV	115 kV
Circuit Breaker line closing switching surge factor	2.2 (i.e. closing resistors required & no restrikes, or line end arresters used to clamp switching over-voltages)	2.2 (i.e. closing resistors required & no restrikes, or line end arresters used to clamp switching over-voltages)	-	-	-
System Grounding	Effectively Grounded Neutral (always)	Effectively Grounded Neutral (always)	Effectively Grounded Neutral (always)	Effectively Grounded Neutral (always)	Effectively Grounded Neutral (always)
Lightning trip out Performance (station)	1/100 yr Keraunic level = 40	1/100 yr Keraunic level = 40	1/100 yr Keraunic level =40	1/100 yr Keraunic level =40	1/100 yr Keraunic level =40
Fault performance (circuit failure, including momentary) all other causes	1/40 yr / breaker position	1/40 yr / breaker position	1/40 yr / breaker position	1/40 yr / breaker position	1/40 yr/breaker position

4.0 Functional Criteria

When evaluating a proposed electrical interconnection, physical as well as electrical characteristics must be considered. This can be done to a certain degree by evaluating the arrangement using the following criteria:

1. The clearing of faulted Interconnection Customer-owned facility equipment, including synchronizing breakers and Interconnection Customer transmission lines, should not adversely affect any TO transmission circuits. This generally means that there could be one or more intertie breakers.

2. Two circuits that feed a common location should not be supplied from a common breaker and a half bay or a common bus such that a single stuck breaker operation would trip both circuits.

3. Multiple ties should be provided between buses for all conditions to ensure network continuity with one transmission breaker out of service.

4. The arrangement of lines and breakers owned by the Interconnection Customer and not under control of PJM shall not allow transmission network load current to flow through the Interconnection Customer's interconnection facilities.

5. A generator radial attachment line shall include a synchronizing breaker or line isolation switch.

6. A transmission line conductor or a static wire that drops within the substation should not cause another transmission circuit to trip.

7. Electrical equipment within the substation must be adequately spaced to:
   - Facilitate equipment maintenance and replacement; and
   - Minimize the likelihood that catastrophic failure of an item of equipment will adversely impact adjacent equipment.

8. In addition to these evaluation criteria the following factors must be reviewed and weighed appropriately in performing the assessment of a substation configuration:
   - Operational complexity and flexibility;
   - Bus load flow balance;
   - Reliability for the load;
   - Reliability for transmission lines;
   - Component reliability;
   - Generator interface;
   - Line maintenance;
   - NERC, MAAC requirements/criteria;
   - Expandability/adaptability;
   - Safety;
   - Fire protection: separation, detection, extinguishing, communication

- Security;
- Spill prevention, control, and countermeasure;
- Changes in technology;
- Cost (capital and O&M); and
- Availability of spare equipment.

5.0 Substation Arrangement

Substations need to be designed to the requirements of the applicable NESC, IEEE, NERC and CIP publications.

5.1 Accessibility and Layout

Adequate space and firm vehicular driving surface must be provided on at least one side of major electrical equipment. This is to permit operations and maintenance vehicles, including bucket trucks and cranes, to the equipment and to maneuver without requiring the de-energization of any adjacent electrical equipment. In a breaker bay this access must be provided the full length of the bay and must not be encumbered by overhead electrical equipment or conductors. Appropriate stone or asphalt roadway must be provided. Breaker bay centerline to adjacent bay breaker centerline distances should be obtained from the Interconnected Transmission Owner.

Electrical equipment must be arranged with adequate clearance for maintenance activities and associated maintenance equipment. Only the equipment to be maintained, the isolating devices, should need to be operated and/or de-energized for the maintenance work to be performed.

Adequate clearance must be provided around the inside of the fence perimeter of the substation for vehicle movement. The corridor must be adequate for the weight of vehicles transporting the heaviest item of electrical equipment installed in the substation.

Unobstructed access must be provided for the substation around the clock. Typically the driveway runs from the entrance to the relay/control house with parking for several vehicles. The entrance gate must be two lanes in width with the yard's safety grounding covering the open gate area.

Control house location needs to be as central to the station as possible. This minimizes unnecessary lengths in protection, control, and auxiliary power conductor. Vehicular approach & access to the Control House must be outside the energized bus area. (Also Ref. Chapter V, Section G)

5.2 Grounding and Fence

An adequate thickness of appropriate crushed stone must be provided for the entire substation site, except where paved, including over the perimeter fence grounding, consistent with the substation owner's grounding design for safe step and touch potential. Grounding must be provided for the entire fenced site including the perimeter grounding outside the substation fence (Ref. IEEE Standard 80).

5.3 Lighting

Adequate lighting must be provided throughout the substation to facilitate the manual operation of electrical equipment at night and perimeter security lighting should be provided.

High mast lighting poles that could possibly fall across electrical equipment shall not be installed.

5.4 Lightning/Surge/Noise Protection

Direct lightning shielding protection shall be provided for all electrical equipment in accordance with the latest revision of IEEE Std. 998 based on the application of Electrogeometric Model (EGM) by the Rolling Sphere or empirical methods in the form of coordinated application of surge arrestors, lightning masts, and static wires.

Control cable shielding must be provided and grounded as appropriate for substations with 100 kV and above voltages.

5.5 Raceways

Typical outdoor main raceway systems consist of pre-cast trench raceway installed either at or below grade with durable fire-resistant covers. Where vehicles must cross raceways, such as a driveway near the relay/control house, suitable covers and construction must be provided for the heaviest vehicle and equipment anticipated to cross the raceway.

Physical separation must be maintained between wiring associated with each battery in multiple battery systems. For new construction, above grade conduit and cable trays shall only be utilized within control house. Indoor conduit and cable trays should be routed to minimize exposure of wiring to fire or explosion associated with electrical equipment. Raceways must be routed perpendicular to the main busses and must not be routed parallel and underneath high-voltage transmission lines.

5.6 Security

Access security at all gates and all doors shall be compatible with the NERC Critical Infrastructure Protection requirements. If an electronic security system is provided there must be provisions for manual entry in the event of loss of power supply. An intrusion alarm system shall be provided as appropriate and compatible with the Transmission Owner’s security system.

5.7 Control House

Control house shall be centrally located to minimize wiring length to electrical equipment. Vehicular approach & access to the Control House must be outside the energized bus area.

The control house should not be located underneath overhead lines.

- The relay/control house must be constructed for long life and minimum maintenance. The local transmission owner must be contacted for specific design requirements, including the need for lavatory facilities, HVAC, and approved construction materials.

- There must be an established demarcation in the relay/control house for leased telecommunication services and phones for the dedicated use of the Transmission Owner. These facilities must be independent of the Interconnection Customer’s facilities. Electrical isolation equipment maybe required for protection of telecommunication devices.

5.8 Auxiliary Facilities