NPPD
White Paper

Customer Owned Generation Ground Fault Overvoltage Analysis

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Nebraska Public Power District
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Executive Summary

With the increase in distributed energy resources (DER) being interconnected by our customers, analysis was performed regarding the risks of islanding and ground fault overvoltage (GFOV) due to faults on the subtransmission system. Following are the key takeaways.

- Islanding can create a serious hazard to personnel, public and equipment as existing protection may not function as designed when generation does not cease to energize the affected area. Anti-Islanding requirements, IEEE 1547 Section 8, are an independent requirement which shall be followed for all new and modified DER installations. This requirement does not address the risks of GFOV. It is unknown whether existing DERs are able to meet IEEE 1547 requirements to prevent islanding.
- GFOV due to a ground fault on the subtransmission system has a high risk of damaging arresters on the subtransmission system when DER remains generating for over one fundamental frequency (16 msec) and can support the load.
- GFOV due to a ground fault on the subtransmission system that exists for greater than two seconds has a risk of damaging power transformers, instrument transformers (voltage and current), voltage regulators (open delta banks), underground cables, and capacitor banks on the subtransmission system when DER remains generating and can support the load.

Reference Documents

IEEE 1547	IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
IEEE C62.92.5	IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems—Part V: Transmission Systems and Subtransmission Systems
IEEE C57.12	IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers
IEEE C57.13	IEEE Standard Requirements for Instrument Transformers
IEEE 2800	IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems
IEEE C37.95	IEEE Guide for Protective Relaying of Utility-Consumer Interconnections

Background

With the creation and evolution of IEEE 1547 there has been industry wide discussion regarding the risk of damaging arresters when interconnected generation does not quickly (< 3 cycles) shutoff when a ground fault occurs on the subtransmission system. In a 3-wire unigrounded (shielded or unshielded) subtransmission system, the GFOV can reach up to 2.0 times nominal line to ground voltage[1] (across arresters) on the subtransmission system.

Figure 1 illustrates the area of concern with a ground fault on the subtransmission system when DER remains generating and can support the load.

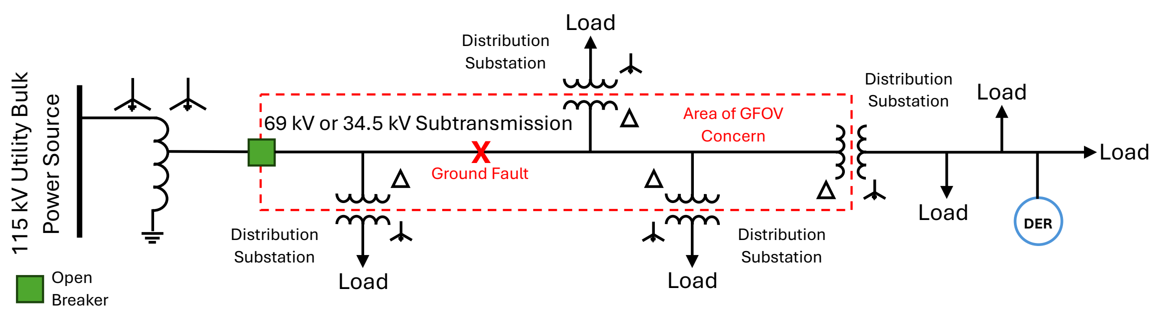

Figure 1. Area of concern due to a ground fault on the subtransmission system.

NPPD and most utilities in Nebraska operate a 3-wire unigrounded (shielded or unshielded) subtransmission system. A graphical representation is shown in Figure 2. Per IEEE 1547, "In three-wire unigrounded systems, a neutral conductor is not run with each circuit, but the system is grounded through the connections of the substation transformer or grounding transformer." The shield wire on the subtransmission system is to protect against lightning surges and is not a neutral conductor for the system.

When a shield wire is not used on the subtransmission lines, arresters may be installed from line to system neutral/ground to protect against lightning. In addition, arresters are always installed from line to neutral in the substations to protect transformers.

Arresters are designed to limit the voltage during a transient overvoltage condition which can occur due to a lightning strike or system switching event. These events typically occur for less than 100 µsec (0.0001 seconds). Due to the extremely short duration the total power dissipated across the arrester is low. GFOV will be continuous until the fault is cleared or generation is removed. Arresters are not designed to withstand GFOV due to the high power dissipation and will suffer catastrophic failure.

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[1] Based on maximum distribution voltage of 1.1 p.u. phase to phase, LTC setting on distribution substation transformer of 1.05 p.u. phase to phase, and conversion of phase to phase voltage to phase to ground voltage of 1.732 for a total GFOV of 2.0 p.u. line to ground.

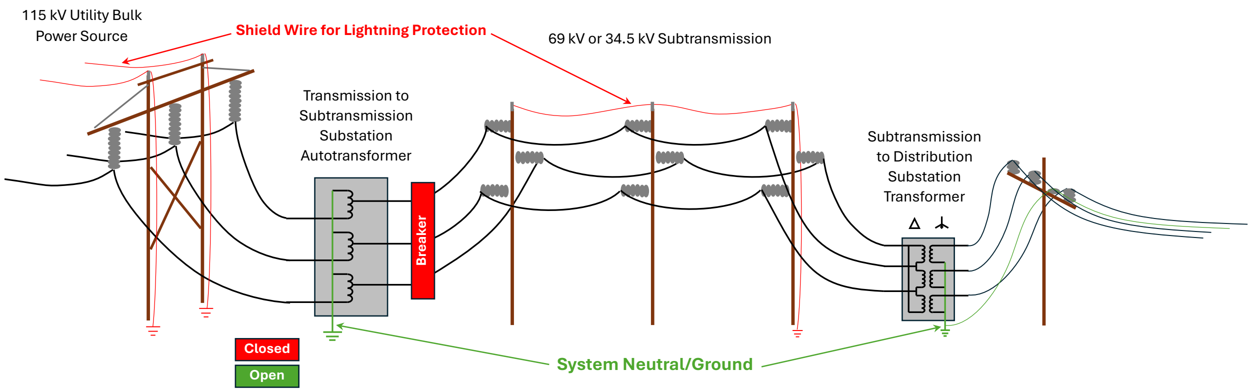


Figure 2. Graphical representation of 3-Wire unigrounded shielded subtransmission system.

In a 3-wire unigrounded (shielded or unshielded) subtransmission system the ground reference is lost when the breaker in the transmission substation opens feeding the radial circuit and no other grounding source is present. The entire area downstream of the open feeder breaker is islanded if DER remains energized in the affected area.

Islanding can create a serious hazard to personnel, public and equipment as existing protection may not function as designed when generation does not cease to energize in the affected area.

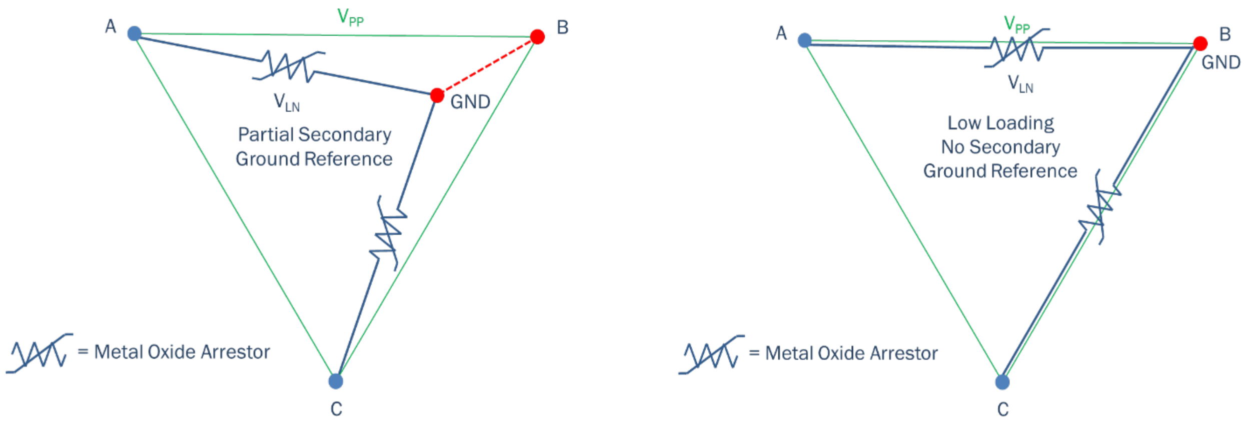
Anti-Islanding requirements, IEEE 1547 Section 8, are an independent requirement which shall be followed for all new and modified DER. This requirement, along with the entirety of IEEE 1547, does not address the risks of GFOV.

IEEE 1547 states that "For an unintentional island in which the DER energizes a portion of the Area Electric Power System (EPS) through the Point of Common Coupling (PCC), the DER shall detect the island, cease to energize the Area EPS, and trip within two (2) seconds of the formation of an island." It is unknown whether DERs constructed prior to 2003 meet this requirement.

Figure 3 illustrates the line to ground voltage during a ground fault with light loading conditions where the ground reference shifts to the faulted phase. Without effective grounding the ground reference can shift entirely to the faulted phase causing a GFOV up to 2.0 times nominal line to ground voltage[1] on the subtransmission system if the DER on the affected system does not trip off or isolate. A recent EPRI presentation[2,3] indicates if DER is 100% inverter based the GFOV level can reach 2.33 times nominal line to ground voltage due to the DER operating as a constant current source.

[2] T. Key, W. Ren, and R. Walling, "Transmission Ground Fault Overvoltage with DER – DER Field Experience Interest Group Meeting #66", EPRI, April 22, 2025

[3] *Understanding Transmission or Sub-Transmission System Ground-Fault Overvoltage.* EPRI, Palo Alto, CA: 2025. 3002033034



(a) **(b)**

Figure 3. Illustration of GFOV (line to ground voltage) due to ground fault on a 3-wire unigrounded (shielded or unshielded) subtransmission system with active DER and light loading; (a) with partial secondary ground reference, (b) no ground reference.

The GFOV is also affected by the total amount of load connected to the island relative to the total amount of generation. To avoid damaging GFOV levels the minimum load to generation ratio shall be 3:1[4,5] for synchronous generators and 1.5:1[6] for inverter-based resources (IBR). To determine the minimum loading for multiple generators it is required to take the sum of each generator nameplate capacity multiplied by the applicable ratio. For example, if there are two (2) diesel generators with nameplate capacities of 2.4 MW and 1.7 MW with an additional solar site with a nameplate capacity of 999 kW the minimum total loading would be as follows.

$$\text{Minimum Total Loading (MW)} = 2.4\text{ MW} * 3 + 1.7\text{ MW} * 3 + 0.999\text{ MW} * 1.5 = 13.8\text{ MW}$$

Low loading refers to load to generation ratios below these levels and high loading refers to load to generation ratios greater than or equal to these levels. These loading levels ensure generation will cease to remain energized, preventing damaging GFOV levels.

Figure 4 illustrates how the nominal phase to phase voltage is reduced under heavy loading conditions as the DER is not able to support the load. The resulting GFOV level is also reduced to levels that will not damage arresters and other equipment on the islanded subtransmission system.

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[4] IEEE 1547.2-2008 “IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems”, 8.4.1, April 15, 2009

[5] W.B. Gish, W.E. Feero, and S. Greuel, “Ferroresonance and Loading Relationships for DSG Installations,” IEEE Transactions on Power Delivery, Vol. PWRD-2, No. 3, July 1987

[6] M. Ropp and A. Ellis, “Suggested Guidelines for Assessment of DG Unintentional Islanding Risk”, Sandia National Laboratories, March 2013

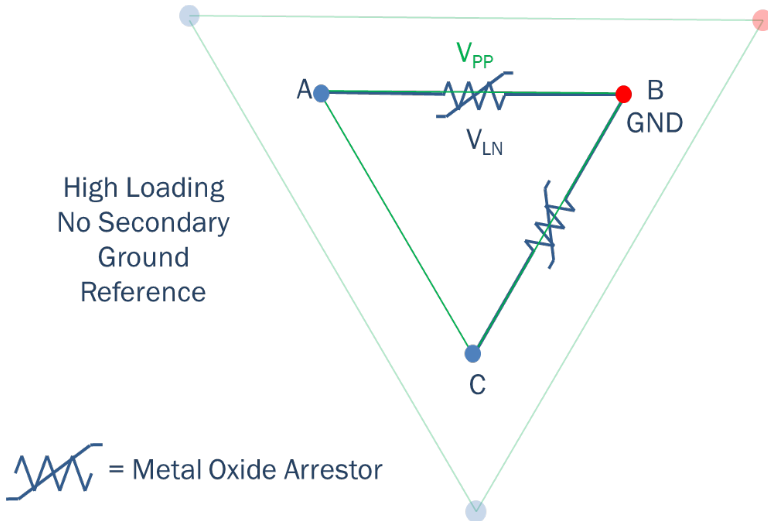

Figure 4. Illustration of GFOV (line to ground voltage) due to ground fault on a 3-wire unigrounded (shielded or unshielded) subtransmission system with active DER and high loading (load to generation ratio ≥ 3:1 for synchronous resources and 1.5:1 for IBR).

When the DER is connected on the distribution circuit there can be distribution voltages exceeding three times nominal voltage due to load rejection overvoltage (LROV) which can damage equipment and create hazards to people if not properly protected. The DER effects on the distribution system are not included in this analysis.

Analysis

The expected maximum[1] GFOV the arresters and other equipment, line to ground, would be exposed to are shown in Table 1.

Table 1. Expected maximum[1] GFOV across arresters (line to ground).

System Nominal Voltage	34.5 kV	69 kV
Maximum GFOV	39.84 kV	79.67 kV

The substation (IEEE C57.12) and instrument (IEEE C57.13) transformers are designed for two times line to ground voltage for at least 30 seconds but at a frequency determined by C57.12.90 section 10.7.2, i.e. ~109 Hz. Aging of the transformer materials will decrease the performance. The industry standard and that of NPPD is to limit the line to ground voltage to less than 1.38 per unit (p.u.). based on effective grounding (IEEE C62.92.5) and IEEE 1547.

The arresters used on the Sub-T system were specified based on a grounded system when the Transmission substation breaker is closed.

Table 2 lists the temporary overvoltage (TOV) rating, line to ground, with prior duty for various subtransmission arresters. Aging of the arrester can further reduce performance. The arresters are unable to survive 2.0 p.u. nominal line to ground voltage for more than a few milliseconds.

Table 2. Various installed subtransmission arrester ratings with prior duty.

Description / Manufacturer	Mfg P/N	MCOV (kV)	TOV Capability (kV/p.u. nominal line to ground voltage)		
34.5 kV System					
ARRESTER, MOV STATION CLASS, 27kV (22.0 MCOV) PORCELAIN			**1s**	**2s**	**10s**
Ohio Brass Co (Hubbell)	VLN027GA022AA	22	32.4/1.63	32.0/1.61	31.1/1.56
General Electric Industrial System	9L11ZGA027AS	22	30.8/1.55	30.4/1.53	29.4/1.47
Cooper Power Systems (Eaton)	AZES004G022027	22	30.8/1.55	30.4/1.53	29.4/1.47
ARRESTER, MOV STATION CLASS, 27kV (22.0 MCOV) POLY					
Cooper Power Systems (Eaton)	UHAA027022A1645A11	22	29.0/1.46	28.6/1.44	27.5/1.38
Hubbell Power Systems	EVP0022003001	22	31.3/1.57	30.9/1.55	29.9/1.50
Hubbell Power Systems	EVP002210-3001	22	31.3/1.57	30.9/1.55	29.9/1.50
ARRESTER, MOV INTERMEDIATE CLASS, 27KV (22.0 MCOV) POLY					
Ohio Brass Co (Hubbell)	300822-3002	22	32.2/1.62	31.7/1.59	30.7/1.54
69 kV System					
ARRESTER, MOV STATION CLASS, 60kV (48.0 MCOV) PORCELAIN			**1s**	**2s**	**10s**
General Electric Industrial System	9L11ZTA060AS	48	67.2/1.69	66.3/1.66	64.1/1.61
Hubbell Power Systems	MVN060GA048AA	48	71.5/1.79	70.6/1.77	68.5/1.72
Cooper Power Systems (Eaton)	AZES006G048060	48	67.2/1.69	66.3/1.66	64.1/1.61
ARRESTER, MOV STATION CLASS, 60kV (48.0 MCOV) POLY					
Hubbell Power Systems	EVP 004800-3001	48	69/1.73	68.1/1.71	66/1.66
General Electric Industrial System	9L11XPA060S	48	65.5/1.65	64.3/1.61	61.4/1.54
Cooper Power Systems (Eaton)	UHAA060048A2845A11	48	63.3/1.59	62.4/1.57	60.0/1.51
ARRESTER,MOV INTERMEDIATE CLASS, 60KV (48.0 MCOV) POLY					
Ohio Brass Co (Hubbell)	PVI 300648-3002	48	70.3/1.76	69.3/1.74	67.0/1.68
General Electric Industrial System	9L12PPA060	48	68.7/1.72	67.7/1.70	65.5/1.64

The voltage-current (V-I) curve provided by Hubbell for arrester EVP004800 is shown in Figure 5. The voltage in these curves is peak voltage as opposed to rms voltage used for the MCOV and TOV ratings. The typical applied peak voltage (nominal line to ground), expected maximum peak GFOV at 2.0 p.u. nominal line to ground voltage, peak MCOV, and peak GFOV with effective grounding at 1.38 p.u. nominal line to ground voltage are shown on the V-I curve. At the peak GFOV with effective grounding level the device is at the knee where the arrester begins to clamp. It can be seen that during the maximum peak GFOV the current through the arrester is 1,000,000 times greater than normal. This causes the power dissipated by the arrester to be over 1,000,000 times greater than normal operation leading to rapid failure with time of exposure. For reference, the peak TOV at two seconds is shown on the V-I curve. Exposure at this voltage level for greater than two seconds will lead to arrester failure.

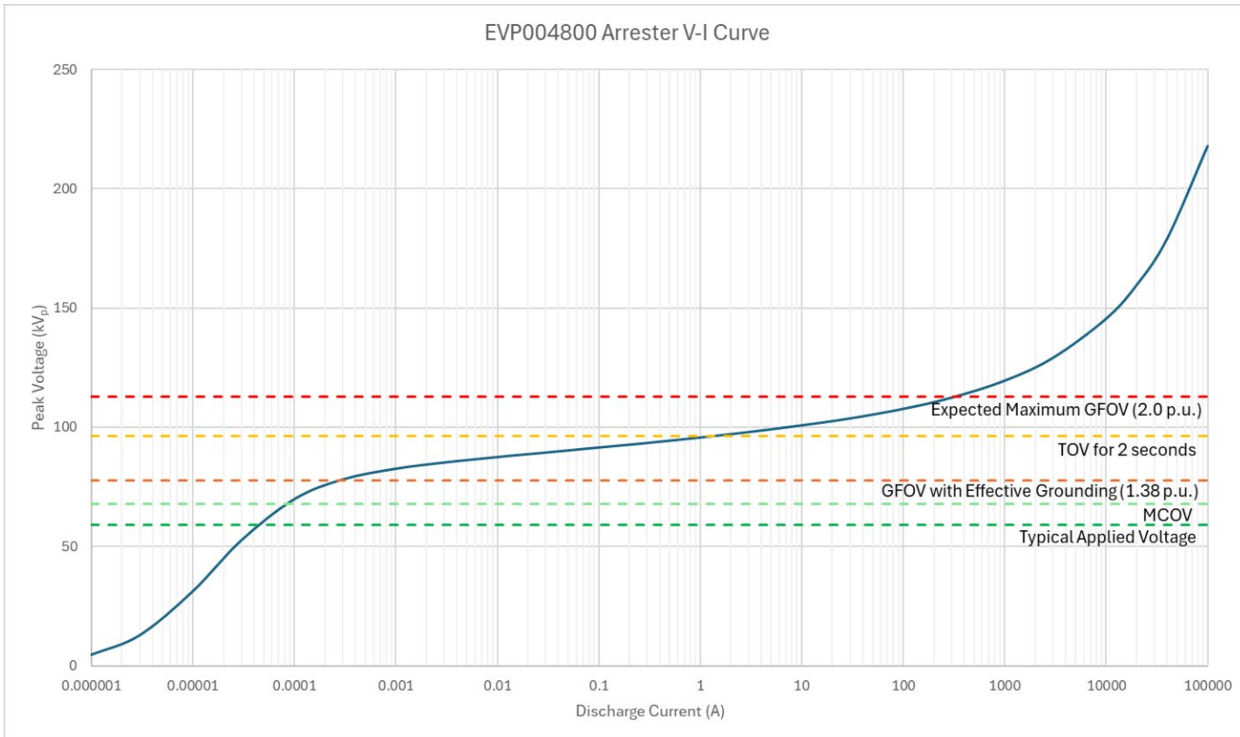

Figure 5. Manufacturer's V-I curve for Hubbell EVP004800 arrester.

Sample modelling was performed to determine if it was possible to accurately determine the expected GFOV level. Many assumptions had to be made due to unknown details reducing the confidence level. The sample model calculated GFOV levels with low loading at approximately 2.0 p.u. on the unfaulted phases, B and C, as shown in Figure 6.

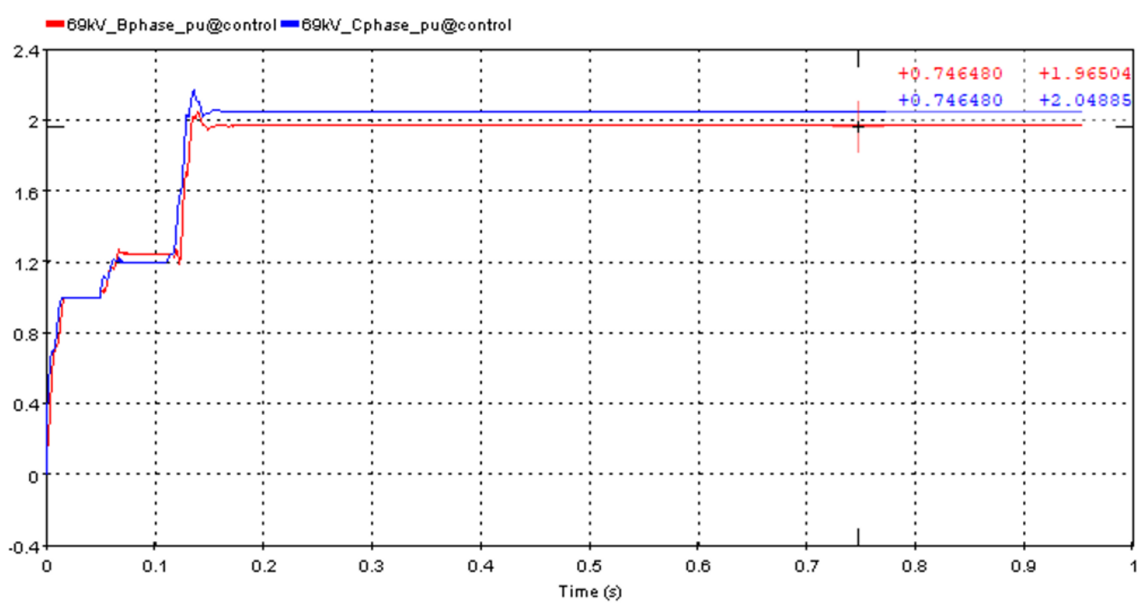

Figure 6. Sample model GFOV levels on the unfaulted phases, B and C, of the subtransmission system.

Increasing the maximum continuous operation voltage (MCOV) of the arresters is not an acceptable mitigation method as it will allow elevated voltage levels during transient events (lightning) which can damage other equipment, e.g. power and instrument transformers, voltage regulators, and capacitor banks.

Using 3V0 with direct transfer trip (DTT) via fiber connection was also analyzed. Typical timing (based on SEL-351-6) for a 3V0 system is provided in Table 3 showing the contribution from each operation. Both a three (3) and five (5) cycle breaker are provided.

Table 3. 3V0 Typical Timing

Operation	**Response Time (Cycles)**	
Relay Processing Interval Time	1	1
Relay Contact Making Time	0.5	0.5
Breaker Trip Time	3	5
Delay Response Time	1	1
Total Clearing Time	**5.5 (91.7 msec)**	**7.5 (125 msec)**

The total time to detect an overvoltage and cease generation would exceed 16 msec as specified in IEEE 1547 section 7.4.1 “Limitation of overvoltage contribution.”

Alternatively, Figure 3 of IEEE 1547 section 7.4.2 “Limitation of cumulative instantaneous overvoltage”, states the maximum cumulative duration for an instantaneous voltage over 1.7 per unit nominal voltage is three (3) milliseconds and over 1.4 per unit nominal voltage is 16 milliseconds. Table 4 provides the number of cycles for the cumulative duration of the overvoltage to exceed these levels given a fundamental frequency GFOV at both the maximum expected level, 2.0 per unit nominal voltage, and a more conservative level of 1.74 per unit nominal voltage.

Table 4. Number of cycles to exceed cumulative overvoltage limits.

Overvoltage Limit (per unit nominal voltage)	**Cumulative Acceptable Time (msec)**	**Number of Cycles to Exceed Limits**	
		2.0 per unit Overvoltage	**1.74 per unit Overvoltage**
1.7	3	1	2
1.4	16	2	3

3V0 protection is not adequate to meet either criteria from IEEE 1547.

Based on the analysis, the acceptable methods for GFOV detection and mitigation are listed in Table 5.

DTT from the transmission feeder prevents the occurrence of GFOV as the generation is tripped offline or isolated prior to opening the transmission feeder breaker, see Appendix A.

The grounding transformer scheme provides effective grounding (< 1.38 pu) until the ground current relay (51N/P) trips the generation offline or isolates the generation. If proper protection of the grounding transformer is not implemented and maintained, the grounding transformer can sustain catastrophic damage during a fault on the subtransmission system.

Table 5. GFOV detection / mitigation methods.

Description	Equipment	Notes	Developer Scope & Cost	NPPD Scope & Charges
Grounding Transformer	Grounding transformer, Recloser or Breaker, one 3 phase CT, one Single CT, relay, and fiber connection to generation site(s)	Grounding transformer shall be specified to reduce GFOV at or below 1.38 p.u. nominal line to ground voltage. 51N and 51P required.	$250,000 - $1,000,000	N/A – NPPD Protection to review scheme, no charges.
Direct Transfer Trip from Transmission Feeder (see Appendix A for concept details)	Dedicated fiber pair connections from transmission feed breaker to each generation site or distribution substation breaker and associated control equipment	Generation with contingency feed not allowed unless fiber connection is present from contingency feed. Loss of communication could cause generation to trip.	Approximately $60,000 per mile (fiber) + $20,000 to $200,000 per site (control hardware and installation). Additional costs may be incurred due to necessary upgrades in the feeder substations.	Protection Engineering checkout, Substation Technician install conduit inside substation and program Transceiver/Receiver. Telecom to terminate fiber pairs $20,000 - $50,000
Power Curtailment with Load Control	RTU and Cellular communication for each generation site.	Loss of communication could cause generation to trip.	Approximately $10,000 - $30,000	Modem, data connectivity costs, Controls Engineering Checkout. Substation Technician to update settings in Substation. $8,000 - $18,000

The DER owners are responsible for anti-Islanding detection, e.g. 27/59/81. Where applicable, DER must be UL1741SB certified. This report is not intended to address anti-islanding.

Appendix A

DTT Concept

Equipment Requirements

- Dedicated fiber pair from transmission feeder (normal and N-1) to each Point of Common Coupling (PCC)/substation or generation site
    - Dedicated pair of fibers for mirrored bits configuration
    - Optional additional fibers, two pair, for metering and curtailment
- Transceiver (SEL-28xx) for each fiber pair at each site (including transmission feeder, normal and N-1)
- Control unit (SEL-2100) at each generation site where more than one disconnect device

Concept Timing Diagram

The timing objective is to allow the POI breaker to open and generation to cease prior to opening the transmission breaker when a fault occurs in order to limit the GFOV to a period less than 16 msec. A conceptual timing diagram of this behavior is shown in Figure A-1.

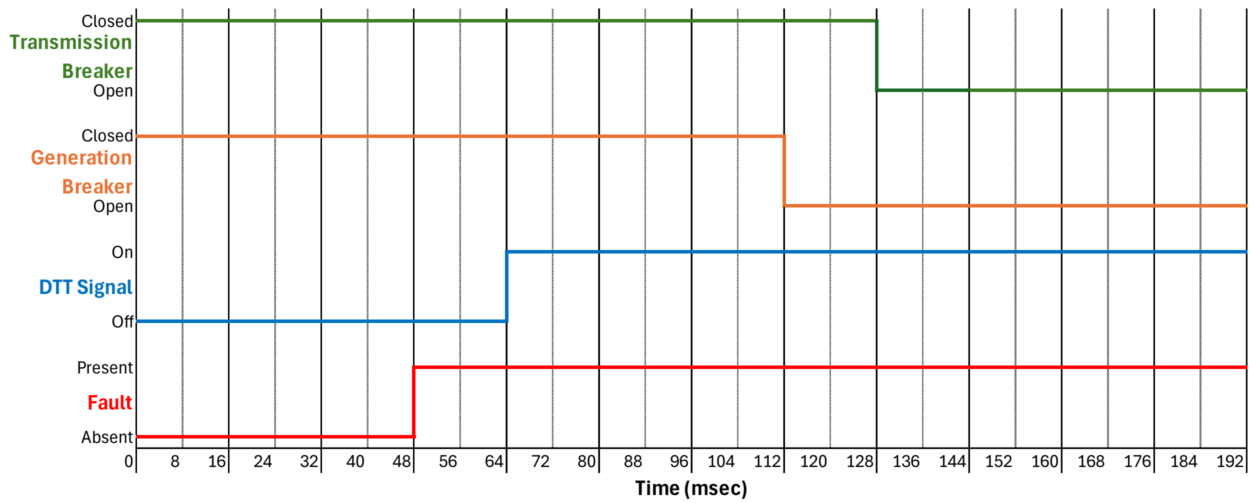

Figure A-1. Conceptual timing diagram when a fault occurs and the resulting DTT signal, PCC breaker, transmission breaker, and generation status.

Concept System Configuration

A dedicated pair of fibers must connect from the normal and contingency (N-1) feeder relay to each PCC and/or generation site. An additional fiber is proposed for curtailment/control communications to ensure the level of generation is at an acceptable level for the real time loading conditions. A conceptual drawing is provided in Figure A-2.

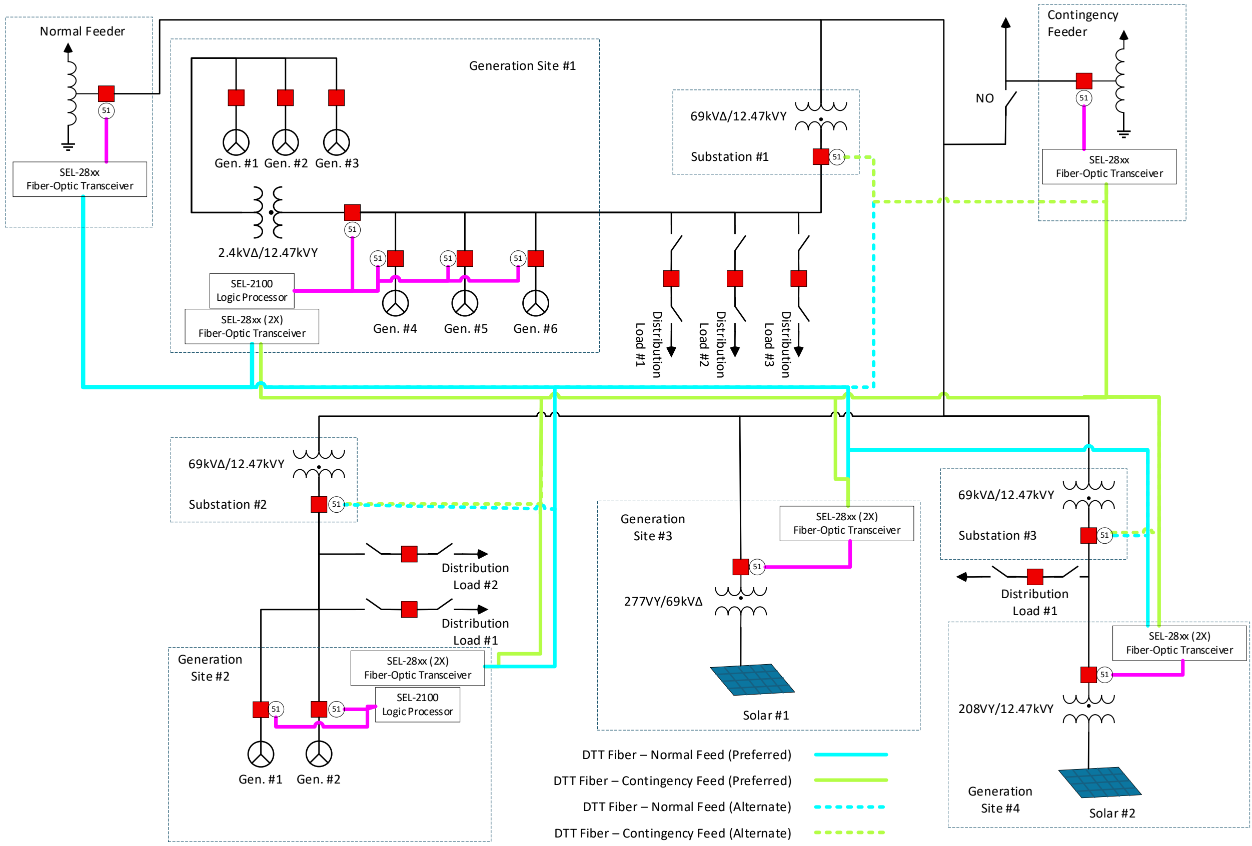

Figure A-2. Conceptual drawing showing the required fiber connections for the system including the PCC substations and generation plants.

Referring to Figure A-2, the preferred option would be to isolate all generators within the generation site by opening the individual breakers within each generation site. An alternate option would be to isolate the entire distribution circuit by opening the breaker in each substation. Provided the latency of the generator breakers is low enough this is the preferred option to mitigate load rejection overvoltage (LROV). It is important that the latency to isolate generation is low enough to open the transmission feeder breaker within a safe period of time to isolate the fault on the subtransmission system.