Generation Line-Tap Connection Impact on Transmission Ground Fault Protection

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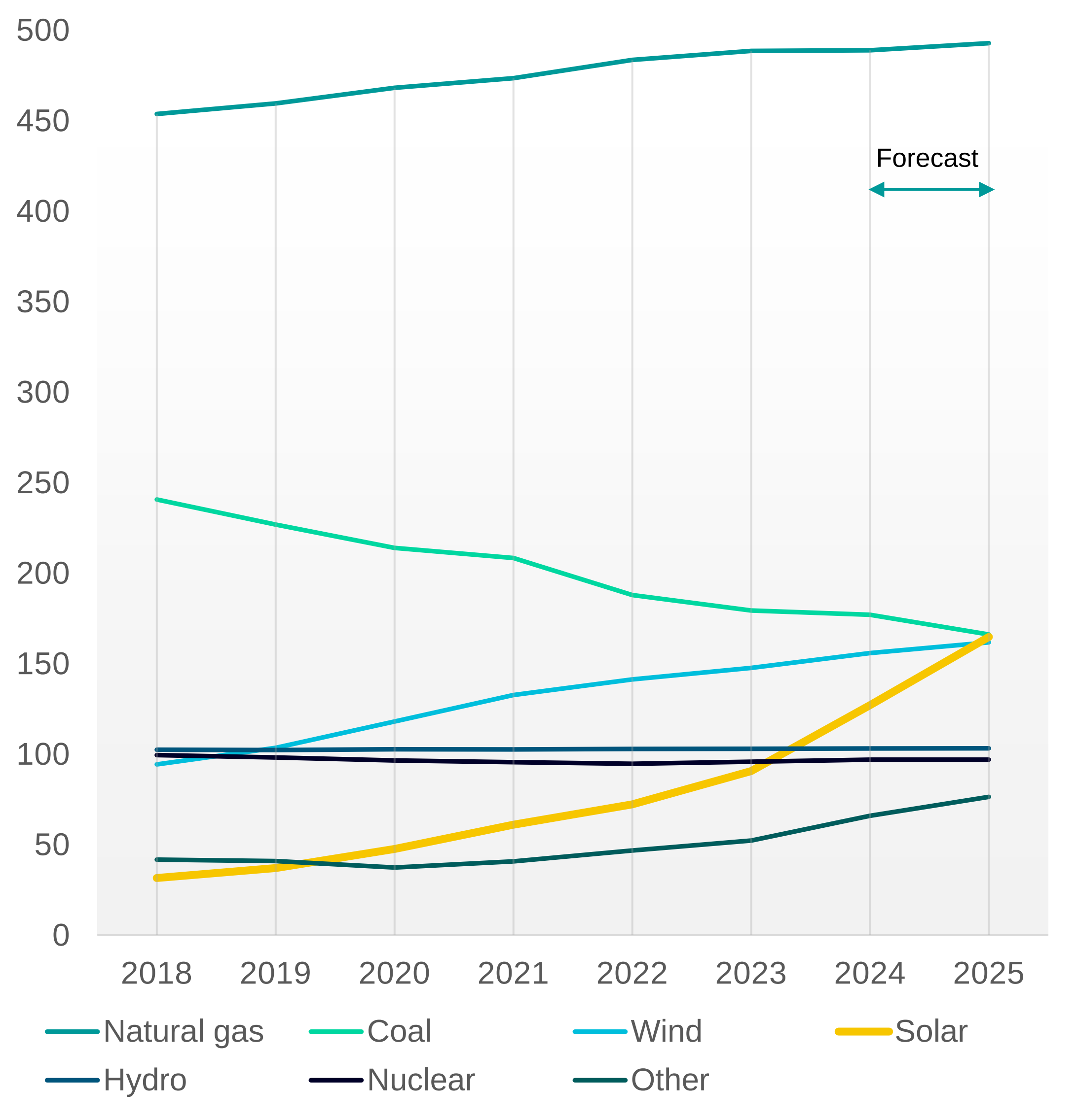
Background and Context

- Transmission interconnection requests for solar generation in the US have been steadily rising
- For small, solar systems near the existing transmission lines interconnecting via a line-tap is a normal practice
- Interconnecting generation systems via a line-tap pose several challenges to existing utility protection systems
- Lack of consistent application of negative-seq. current requirements from Inverter-based-Resources (IBRs) for ground fault detection and protection
- A US case study of solar plant that interconnects with an existing transmission line via a line-tap
- Challenges, lessons learned, and potential solutions to address above challenges are discussed in the paper

US Annual Electricity Gen. Capacity in GW (2018–2025)



Source: US EIA

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Protection Challenges

- Weak transmission grids pose protection challenges for generation systems interconnected via line-taps
- Line-tap connections can reduce line-end zero-sequence current contribution, affecting ground overcurrent relay sensitivity
- Changes in transmission line apparent impedances can lead to relay zone overreach issues
- Transmission system owners may stipulate costly three-breaker-ring connections to mitigate these challenges

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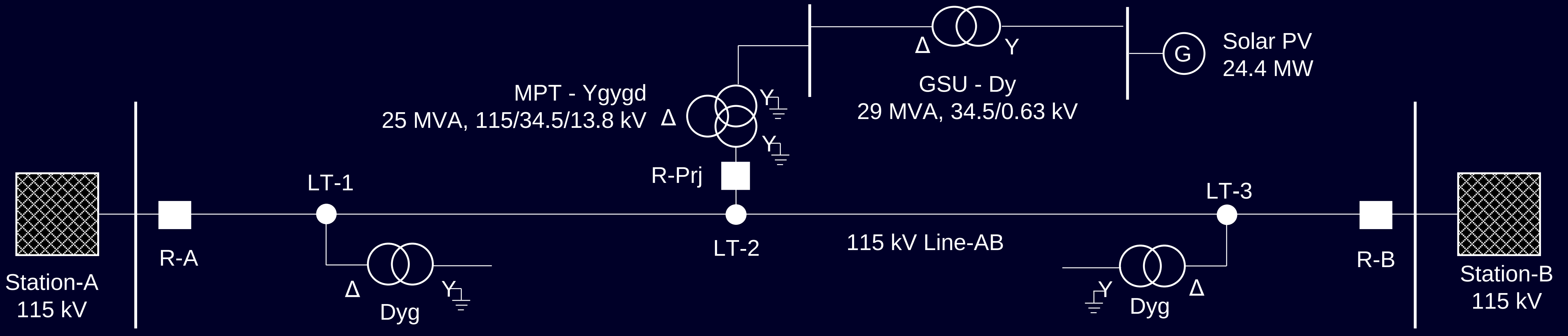
Study Project – Overview



Project single-line diagram

- 24 MW solar farm:116x210 kVA, 630 V PV IBRs
- Solar plant max. short-circuit current contribution was approx. 110% of the nominal current value
- 115 kV OHL Line-AB (82.7 km) tapped at LT-2 for the proposed solar site
- Relays R-A and R-B protect Line-AB and other tapped interconnections
- Upon R-A or R-B activation, a Direct Transfer Trip (DTT) signal is sent to solar plant to trip the site
- Station-A is a weak source of SLG fault current

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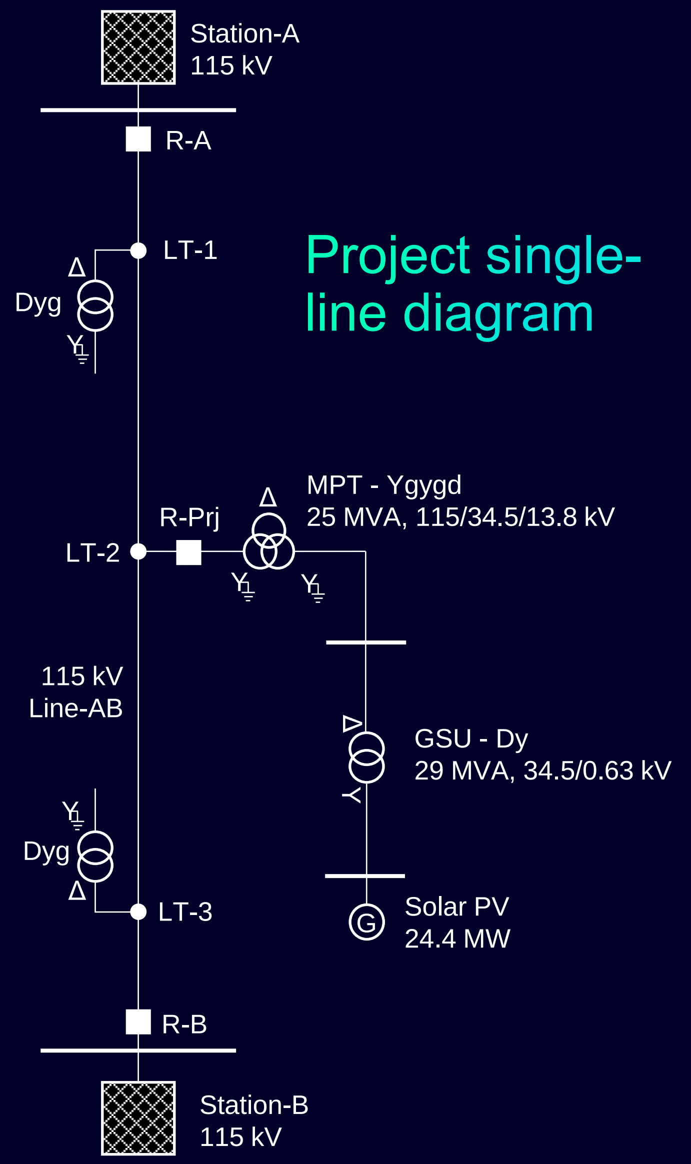
Study Project – Challenges

- Station-A is a weak source of SLG fault current
- Solar site MPT's 115 kV solidly-grounded Y-side is expected to provide current infeed, affecting the apparent impedance of the ground distance protection relays R-A and R-B
- With solar interconnection, relay R-A has a diminished ability to reliably detect ground faults:
  - ISO requires the relay R-A to see at least twice (160 A) the relay's minimum pickup value (80 A)
  - Variation in ground distance relay-related impedances
- Solar IBRs, combined with their Dy transformers, during fault conditions, are not a continuous source of significant zero-seq. or negative-seq. currents—site is unable to detect SLGs on the Line-AB

Project single-line diagram



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Study Project – Methodology

- ISO’s ASPEN short-circuit Base Case transmission system models, with the solar site plant, were obtained, reviewed, and used
- Reviewed ISO's 2019, 2022, and 2027 base cases, comparing the short-circuit levels near project areas
- Studies focused on classical, bolted SLG faults and related impacts
- Simulated potential Station-A short-circuit contributions for SLG faults at Station-B in pre- and post-project scenarios
- For post-project scenario, studies evaluated the impact of impedance grounding of the MPT 115 kV Y-side for various NGR sizes

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Study Project – Methodology (Cont'd.)

- Calculated apparent impedances of relay R-A for SLG faults at Station-B and analyzed ground distance relay responses
- Investigated the potential impact of continuous negative-sequence short-circuit currents from solar inverters in various ISO base cases
- Conducted simulations for different slopes of positive- and negative-sequence dynamic reactive currents and analyzed obtained results

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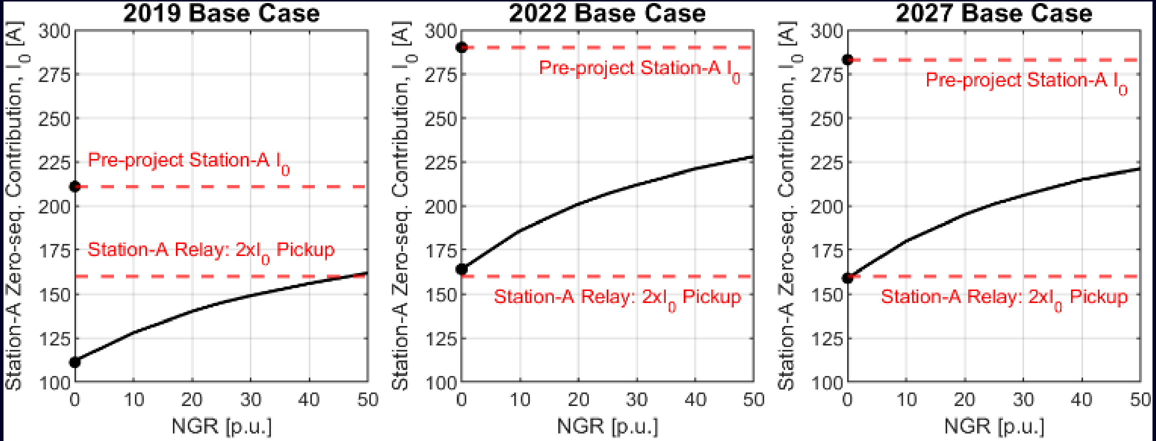
Review of ISO Base Cases' Short-Circuit Levels

- Short-circuit analysis of the ISO's 2019, 2022, and 2027 bases cases was performed
- Two scenarios, pre-project (before project connection) and post-project (with the project connected to the model), were considered
- Bolted three-phase-to-ground (3LG), two-phase-to-ground (2LG) and SLG faults were applied at nine principal nodes in the vicinity of the project location
- Short-circuit contributions at the selected principal nodes, for the considered fault types, were generally higher than those short-circuit contributions in the ISO 2019 Base Case than for other cases

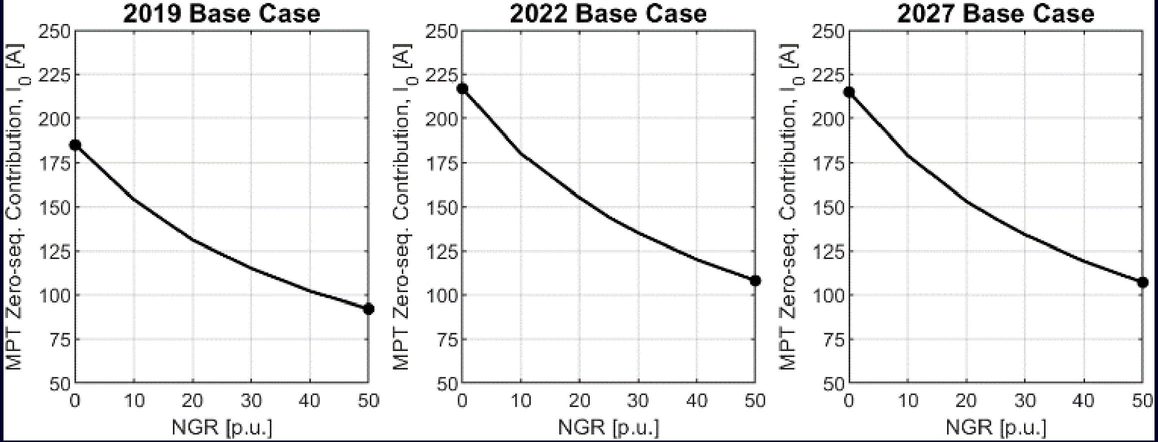
Short-Circuit Levels (SCLS) Between ISO Base Cases

ISO Base Case	ISO's Nodes	Pre-project SC Levels			Post-project SC Levels		
		3LG	2LG	1LG	3LG	2LG	1LG
2022 BC SCL increase against the 2019 BC	Node 1	18%	18%	6%	18%	16%	8%
	Node 2	6%	9%	21%	6%	9%	20%
	Node 3	5%	8%	21%	5%	8%	20%
	Node 4	5%	8%	21%	5%	8%	20%
	Node 5	6%	9%	21%	6%	9%	20%
	Node 6	6%	9%	21%	6%	8%	20%
	Node 7	-5%	-4%	-4%	-5%	-4%	-4%
	Node 8	8%	6%	6%	7%	6%	6%
	Node 9	7%	6%	6%	7%	6%	6%
2027 BC SCL increase against the 2019 BC	Node 1	9%	9%	3%	9%	8%	4%
	Node 2	8%	11%	24%	8%	11%	24%
	Node 3	8%	11%	24%	8%	11%	24%
	Node 4	8%	11%	24%	8%	11%	24%
	Node 5	8%	11%	24%	8%	11%	24%
	Node 6	8%	11%	24%	8%	11%	24%
	Node 7	-5%	-4%	-4%	-5%	-4%	-4%
	Node 8	27%	23%	22%	27%	22%	22%
	Node 9	25%	21%	21%	25%	21%	21%

Zero-Seq. Short-Circuit Current Contributions



a. Station-A zero-seq. short-circuit current contributions



b. MPT's 115-kV side zero-seq. short-circuit current contributions

Short-circuit contributions for various MPT NGR sizes

- Zero-seq. current contributions (I_0) from Station-A and MPT's 115 kV terminal were measured for varying NGR sizes (including when the NGR was bypassed)
- Zero-seq. currents varied between the considered ISO Base Cases

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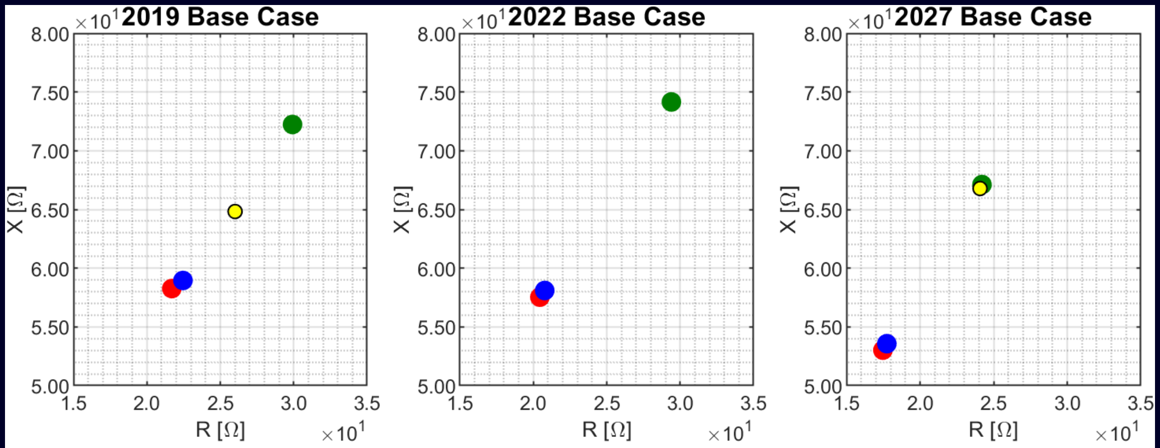
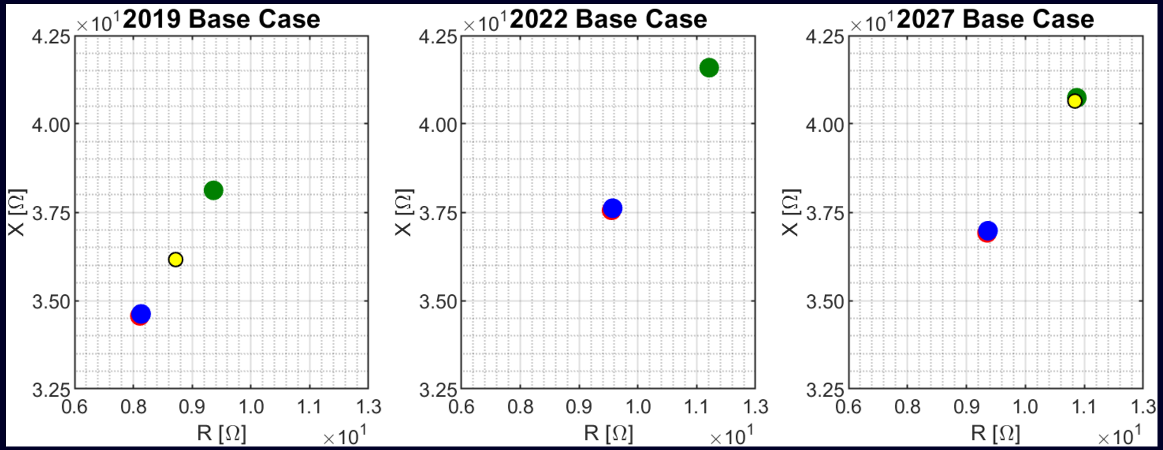
Zero-Seq. Short-Circuit Current Contributions (Cont’d.)

- In ISO 2019 Base Case, with and without project connected and MPT's 115 kV side grounded, Station-A's contributions were 210 A and 111 A, respectively—111 A is less than twice the relay pickup value
- In ISO 2019 Base Case, with the project connected and MPT's 115 kV side grounded with NGR and only when NGR = 50 p.u., Station-A’s I_0 reached above twice the relay R-A pickup value
- In ISO 2022 and 2027 Base Cases with the project connected and MPT's 115 kV Y-side grounded, Station-A's contributions were close to or above the twice the relay R-A pickup value—needing minimum NGR size or no NGR for a proper relay R-A operation:
  - MPT's zero-seq. contributions within acceptable ranges for various NGR sizes
  - With project connected and MPT's 115 kV Y-side ungrounded, Station-A's contributions exceeded threshold values, remaining consistent across base cases

Ground Distance Relay-Related Impedances



a. Line-AB apparent impedances, as seen by R-A relay, for a SLG fault at Station-B



b. Line-AB apparent impedances, as seen by R-B relay, for a SLG fault at Station-A

Apparent impedances measured by the line-end ground distance relays for the considered SLG faults

- Study conducted for ISO's 2019, 2022, and 2027 Base Cases, analyzing the ground distance relays R-A and R-B impedances for SLG faults at Station-B and Station-A, respectively
- Relay R-A and R-B apparent impedances vary conditions of project connection or not and MPT grounding scenarios if the project is connected

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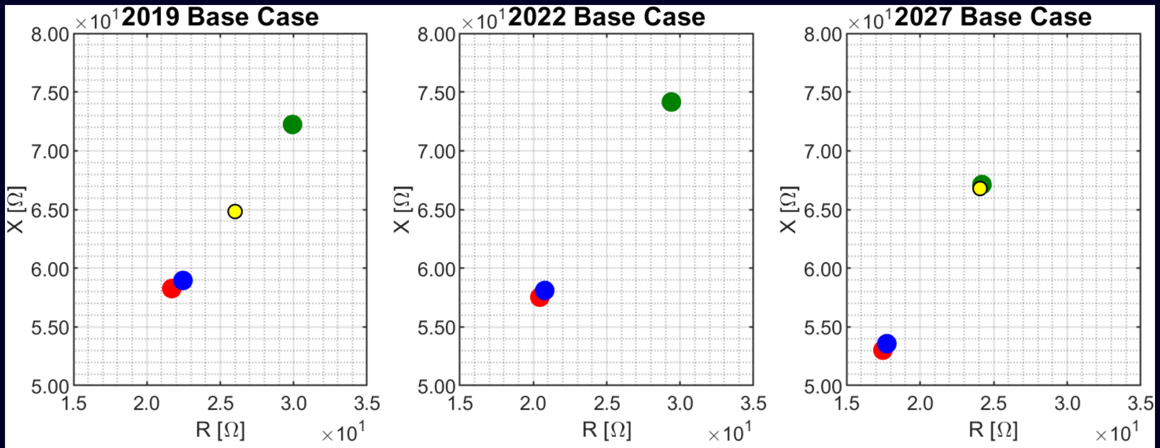
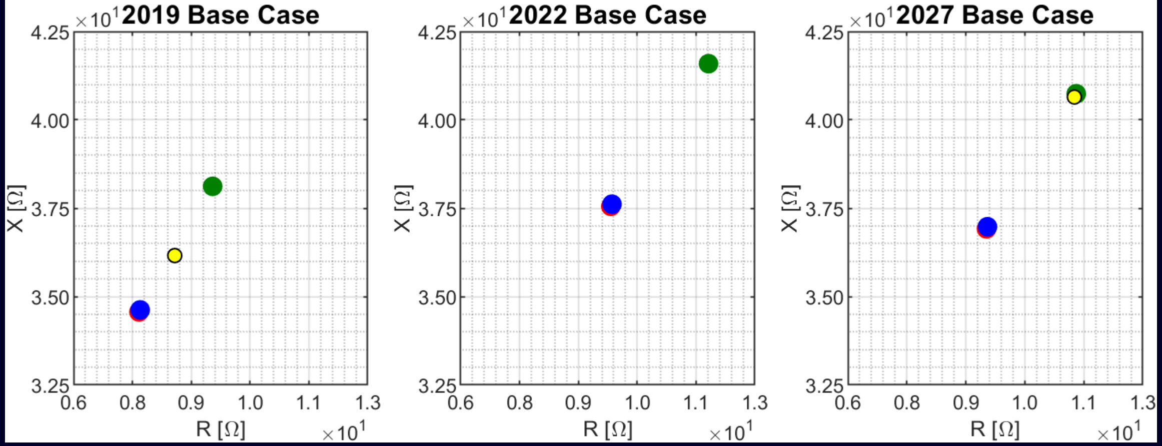
Ground Distance Relay-Related Impedances (Cont’d.)



a. Line-AB apparent impedances, as seen by R-A relay, for a SLG fault at Station-B



b. Line-AB apparent impedances, as seen by R-B relay, for a SLG fault at Station-A

Apparent impedances measured by the line-end ground distance relays for the considered SLG faults

- Operating the project with MPT's 115 kV Y-side ungrounded results in no significant impedance changes: see red (without project) and blue (with project) dots
- Project connection to ISO's system alters apparent impedances seen by ground distance relays (red and green dots in Figure 3), necessitating review of relay settings

Ground Distance Relay-Related Impedances (Cont'd.)

ISO Base Case	SLG Fault Location	MPT Grounding	Sequence Voltages			Line-to-Gnd. Voltages		
			Pos. Seq. (kV)	Neg. Seq. (kV)	Zero Seq. (kV)	Phase-A (%)	Phase-B (%)	Phase-C (%)
2019	Station-A	Ungrounded	54.3	10.9	30.6	19%	**117%**	**115%**
		NGR=50 p.u.	53.8	11.4	27.6	22%	**114%**	**111%**
	Station-B	Ungrounded	56.9	8.3	9.0	60%	100%	98%
		NGR=50 p.u.	56.9	8.3	7.8	62%	99%	97%
2022	Station-A	Ungrounded	56.5	10.1	33.8	19%	**121%**	**123%**
	Station-B	Ungrounded	59.0	7.5	10.7	62%	103%	102%
2027	Station-B	Ungrounded	56.0	10.7	33.7	18%	**121%**	**122%**
		NGR=1 p.u.	54.9	11.8	26.7	25%	**114%**	**112%**
	Station-B	Ungrounded	58.9	7.7	10.6	61%	103%	102%
		NGR=1 p.u.	58.9	7.7	7.6	66%	101%	99%

Post-project: MPT'S 115 kV Y-side during-fault voltages

- SLG faults at Station-A with ungrounded MPT or selected NGRs lead to line-to-ground voltages exceeding equipment tolerances, requiring protection with R-Prj relay's phase overvoltage element (59)
- Voltages at 115 kV side of MPT within typical relay pickup settings for negative-sequence and zero-sequence voltages under selected operating scenarios

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Negative-Seq. Short-Circuit Current Contributions

- IBRs do not typically or do not consistently contribute negative-sequence currents during external unbalanced faults
- Evaluation of negative-sequence short-circuit current contributions considered various slopes of negative-sequence dynamic reactive current (*k* values 2–6)
- Simulated site MPT's 115 kV positive- and negative-sequence short-circuit currents for different solar inverter *k* values and SLG faults at Station-B

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Neg.-Seq. Short-Circuit Current Contributions (Cont'd.)

ISO Base Cases	Pos. Seq. Currents (A)					Neg. Seq. Currents (A)				
	k=2	*k*=3	*k*=4	*k*=5	*k*=6	*k*=2	*k*=3	*k*=4	*k*=5	*k*=6
2019	37.3	49.9	53.6	-	-	20.7	27.3	25.5	-	-
2022	38.5	52.2	63.3	65.0	75.3	20.2	26.7	32.7	27.4	67.1
2027	37.2	50.5	71.0	-	-	18.1	25.6	37.8	-	-

Post-project: MPT'S 115 kV short-circuit contributions

- Results show that higher *k* values lead to higher inverter negative-sequence short-circuit current contributions and higher terminal voltages.
- In cases where inverter terminal voltages exceeded 1.1 p.u., inverters shutdown, resulting in no short-circuit contributions
- The choice of *k* value should be determined during project design or as part of the ISO's SIS
- Simulated negative-sequence short-circuit current contributions were within typical relay pickup setting ranges

Potential Mitigation Options

Option-1: Consideration of ungrounded operation with voltage element detection:

- Operate the site's MPT's 115 kV Y-side as ungrounded
- Use ground fault detection using the site relay's voltage elements as secondary protection
- Implement the utility's signal-based DTT primary protection
- The existing ground distance relay settings at Station-A may remain suitable since the apparent impedance seen by the ground distance relay won't change significantly

Option-2: Solidly or impedance grounding with current element detection:

- Ground the site MPT's 115 kV Y-side solidly or with impedance grounding
- Utilize ground fault detection using the site relay's current elements as secondary protection
- Implement the utility's signal-based DTT primary protection
- Review and potentially redefine Station-A ground distance relay settings, considering apparent impedance changes due to the site's connection

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Potential Mitigation Options (Cont’d.)

Option-3: Utilization of negative-seq. protection for projects with negative-seq. current injection:

- For projects with significant negative-sequence current injection capability, utilize the site MPT's 115 kV Y-side negative-sequence protection elements.
- Determine a suitable k value for the project in advance

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Key Takeaways

- Presented options underscore the importance of considering various factors such as project equipment, system setup, protection philosophies of host utilities, and operational criteria and constraints of the ISO's system
- The choice of mitigation strategy would depend on the specific characteristics and requirements of the project, as well as the broader system considerations outlined above
- Standardization and consistent application of negative-seq. current requirements from IBRs for ground fault detection and protection is necessary for broader adoption of IBRs

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Questions?

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