Alternate Mitigation and Design Options to 3V0 Requirement

Under Contract PON 3404-111076

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Objectives

- Identify an alternative to the 3V0 scheme that is more cost effective and can respond faster in mitigating GFOV
- Discuss background and simulation results for negative sequence voltage (NSV) protection scheme

PART 1- Alternate to traditional 3VO Scheme

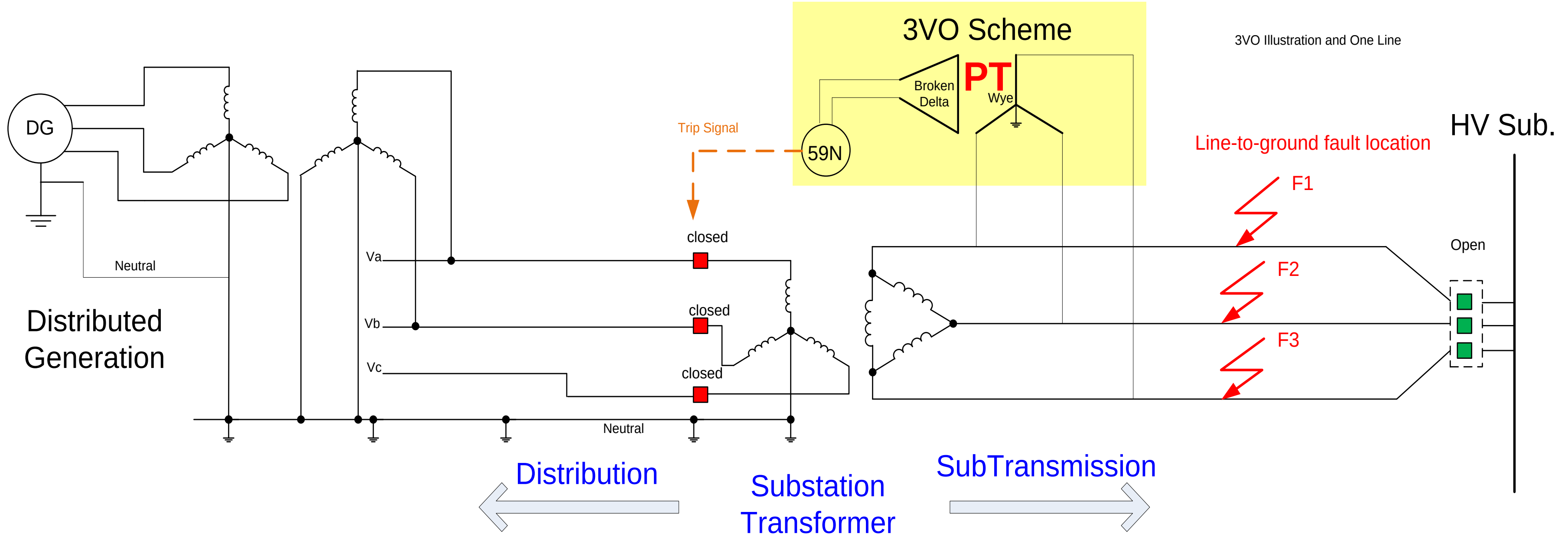
- Additional Guidance to PV Developers and Utilities
- Provide future design options that will prevent or mitigate the GFOV issue

PART 2

PART 1 – Alternate Mitigation to 3VO Scheme

Traditional 3V0 Scheme

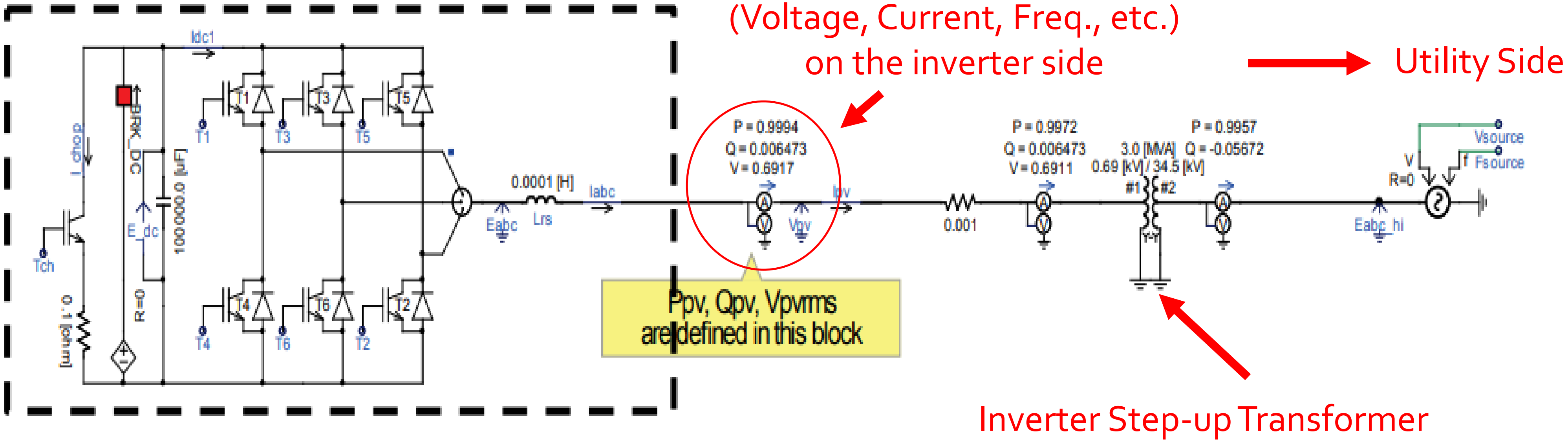
- GFOV occurs for Fault F1,F2, or F3 – breaker open , no grounding source and not enough loads to depress overvoltage
- One mitigation measure for GFOV is to add PTs on the transformer delta (high) side
- The PTs measure the 3V0 voltage to identify an overvoltage
- Relays send signals to trip DG or feeder breaker to eliminate the overvoltage



Alternative to 3V0 Scheme

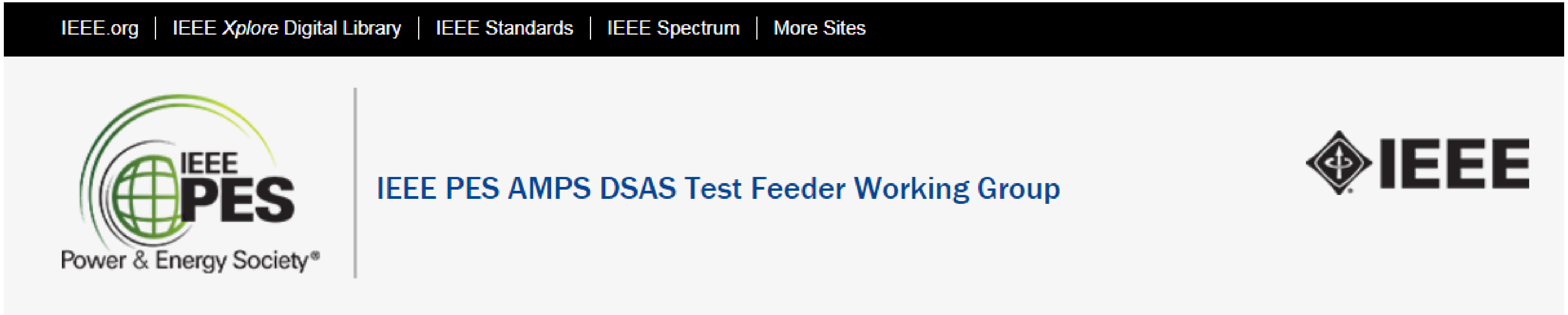
Goals: cost effective & respond faster

- Detect SLG fault on subtransmission from the distribution side / inverter side
- Detect SLG as it happens
- Should not operate during normal switching events: load switching, cap bank switching, motor starting

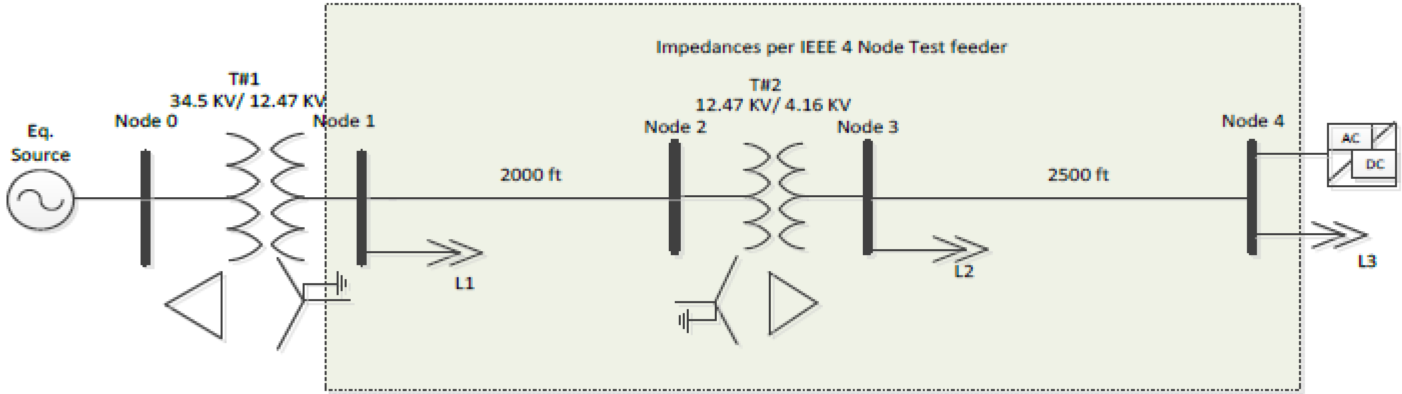


Grid / Distribution Feeder Model

- Four test feeders
  - Test Feeder #1: IEEE 4 Node Feeder , modified to 5 nodes to include Substation Transformer
  - Test Feeder #2: 12 km long, 25 kV Radial Feeder
  - Test Feeder #3: IEEE 13 Node Feeder (Short Feeder)
  - Test Feeder #4: IEEE 34 Node Feeder (very Long Feeder, Actual feeder located in Arizona)



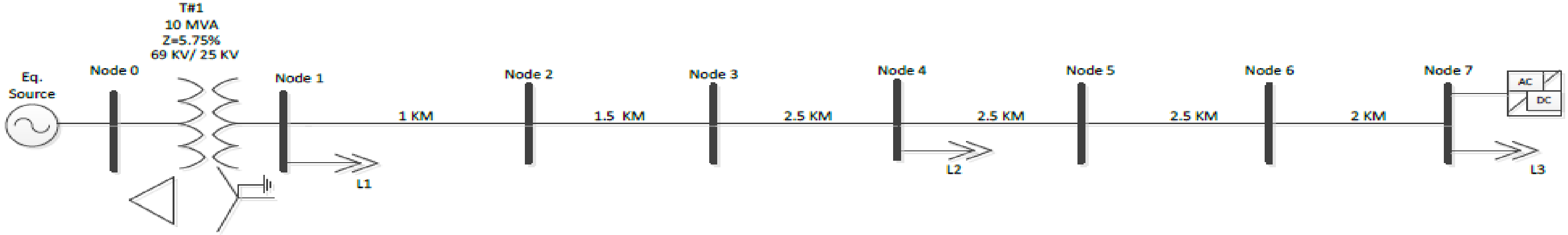
Grid Model – Test Feeder #1 (IEEE 4 Node Feeder)



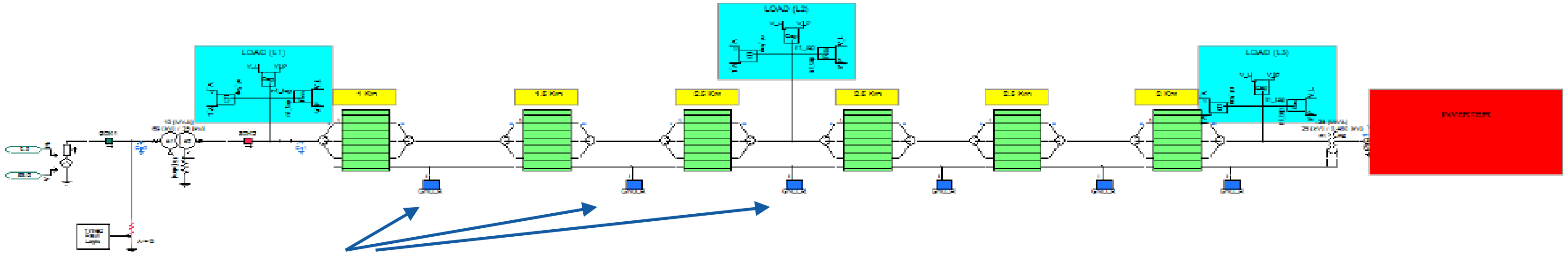
- This feeder is an extended version of the IEEE 4-node test feeder.
- A fifth node was added in order to include a 34.5 kV/12.47 kV delta-wye substation transformer in the model.
- Inverter-based PV is located at node 4, the furthest node from the substation transformer.

Grid Model– Test Feeder #2 (from IEEE Journal)

10 MVA, 69/25 kV

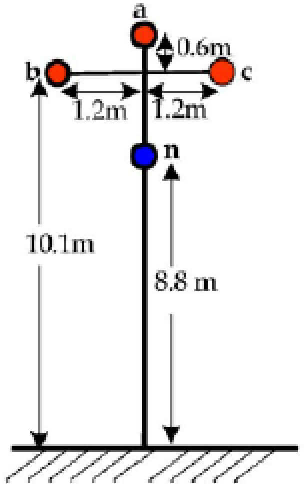


(a) schematic of the Circuit



Multi-grounded, 7 ohm resistance

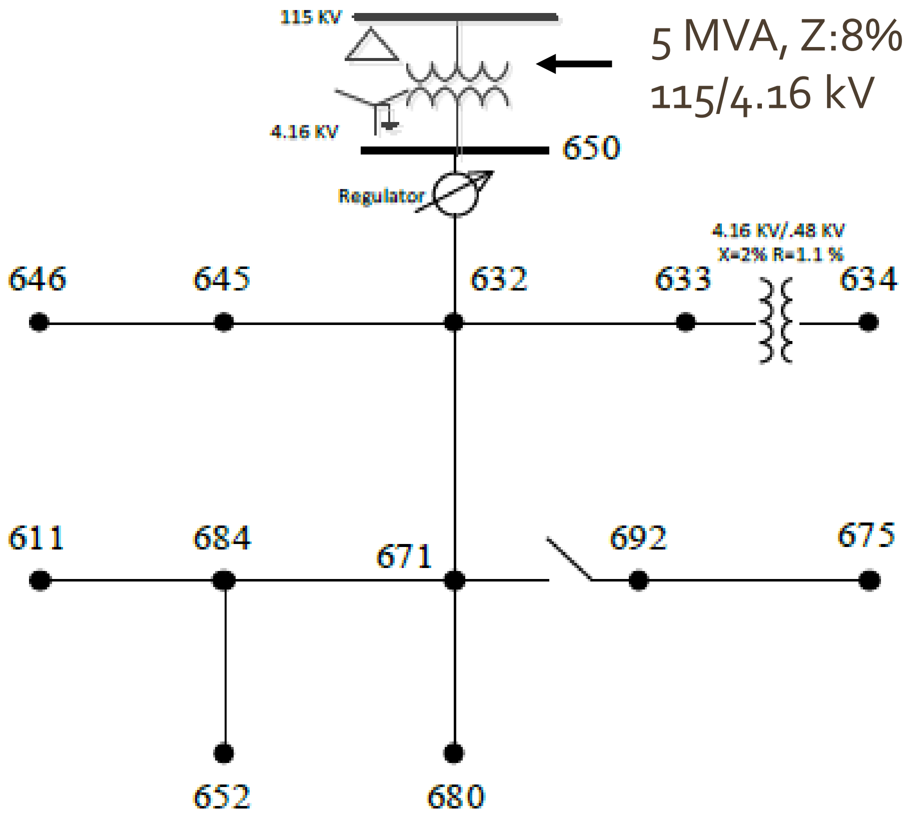
(b) Top View of the PSCAD Model



Conductor	Diameter	Resistance Ω/KM	Self-Impedance Ω/KM	Mutual-Impedance Ω/KM
Phase: 3/0 Pigeon	12.75 mm	.3375	.396+j.912	.058+j.493(phase-to-phase)
Neutral: #2 Haddock	7.8 mm	.8530	.911+j.946	.058+j473 (phase-to-neutral)

- Based on a research documented in IEEE Journal
- Unique: four-wire multi-grounded circuit
- Neutral conductor is modeled explicitly (no Kron Reduction)
- Pole grounds are modeled with 7 ohms resistance

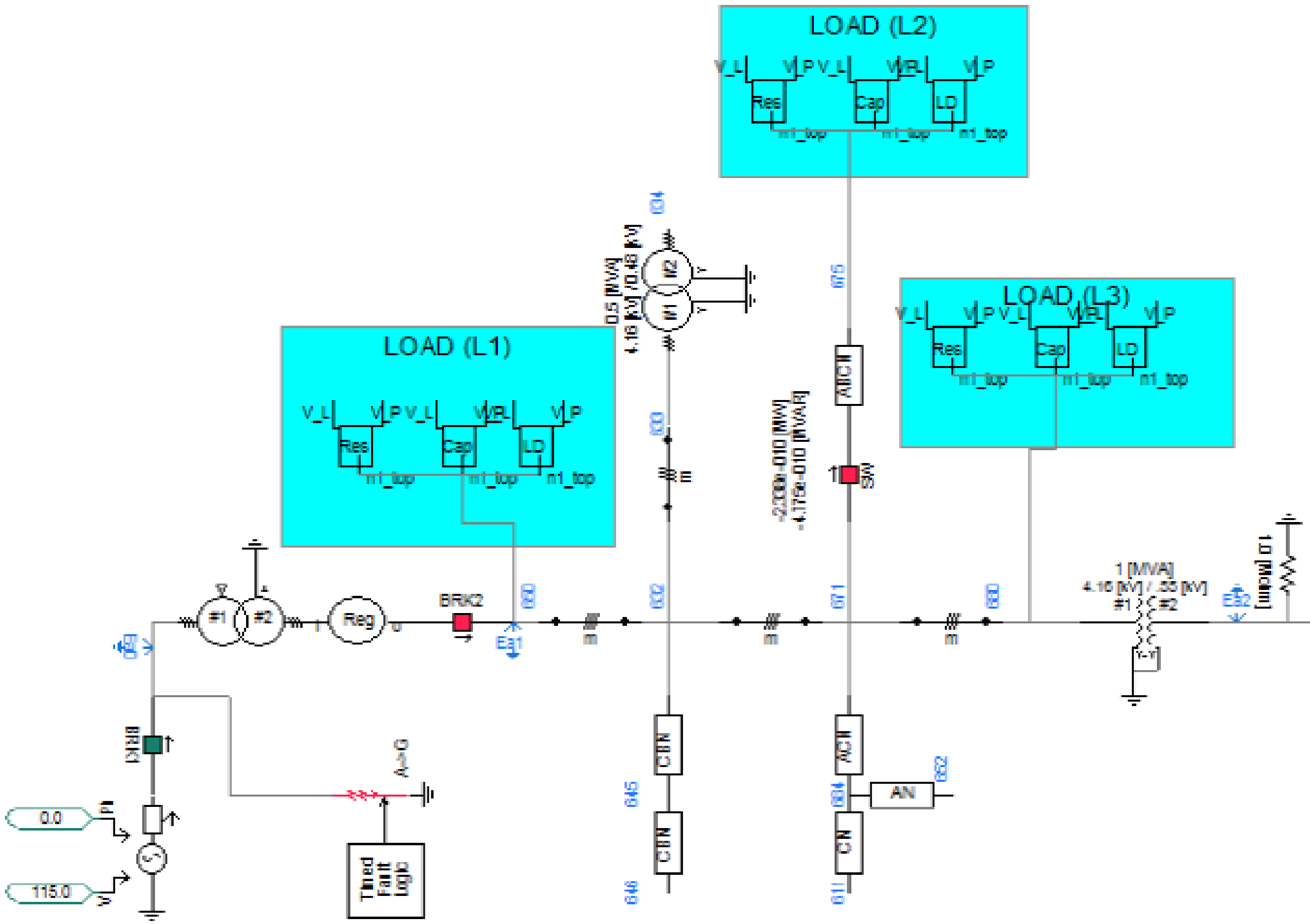
Grid Model – Test Feeder #3 (IEEE 13 Node Feeder)

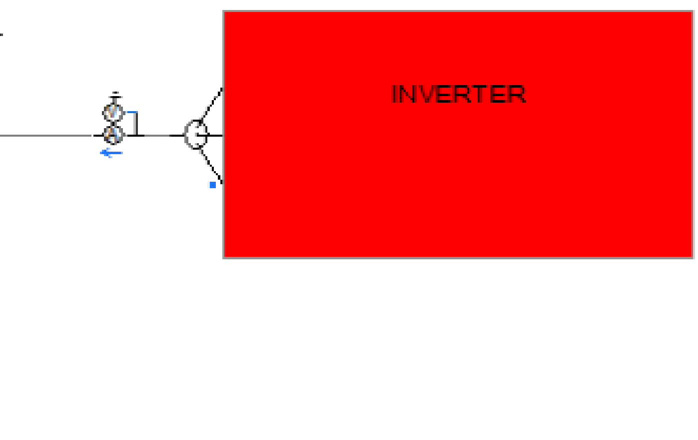


- Short 4.16 kV Feeder with voltage regulator
- Combination of overhead (OH) and underground(UG) line with
- Variety of phasing: 3 phase, phase-to-ground, phase-phase-to-ground
- Connected to 115 kV transmission system through 5 MVA delta – wye_grounded transformer with Z=8%

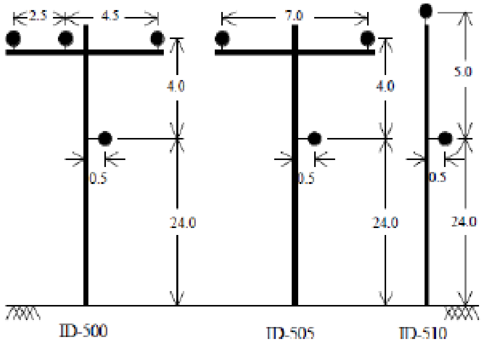
Node A	Node B	Length (ft.)	Config.	ID	Phasing	Impedance matrix *Z (R +jX) in ohms per mile*[8]
632	645	500	603	505	OH/ C B N	0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 1.3294 1.3471 0.2066 0.4591 1.3238 1.3569
645	646	300				
632	633	500	602	500	OH/ C A B N	0.7526 1.1814 0.1580 0.4236 0.1560 0.5017 0.7475 1.1983 0.1535 0.3849 0.7436 1.2112
650	632	2000	601	500	OH/ B A C N	0.3465 1.0179 0.1560 0.5017 0.1580 0.4236 0.3375 1.0478 0.1535 0.3849 0.3414 1.0348
632	671	2000				
671	680	1000				
671	684	300	604	505	OH/ A C N	1.3238 1.3569 0.0000 0.0000 0.2066 0.4591 0.0000 0.0000 0.0000 0.0000 1.3294 1.3471
684	611	300	605	510	OH/ C N	0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 1.3292 1.3475
692	675	500	606	515	UG/ A B C N	0.7982 0.4463 0.3192 0.0328 0.2849 0.0143 0.7891 0.4041 0.3192 0.0328 0.7982 0.4463
684	652	800	607	520	UG A N	1.3425 0.5124 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000

Grid Model – Test Feeder #3 (IEEE 13 Node Feeder)



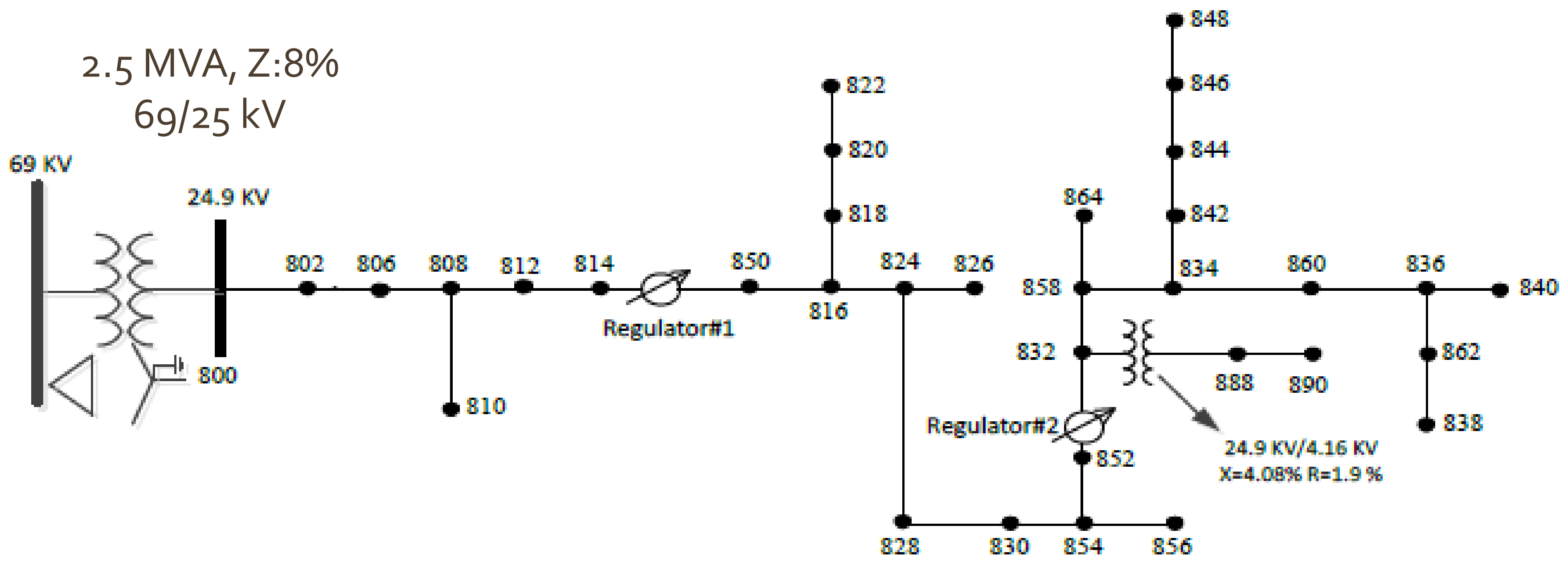


Overhead Conductor Spacing



Underground Conductor Spacing

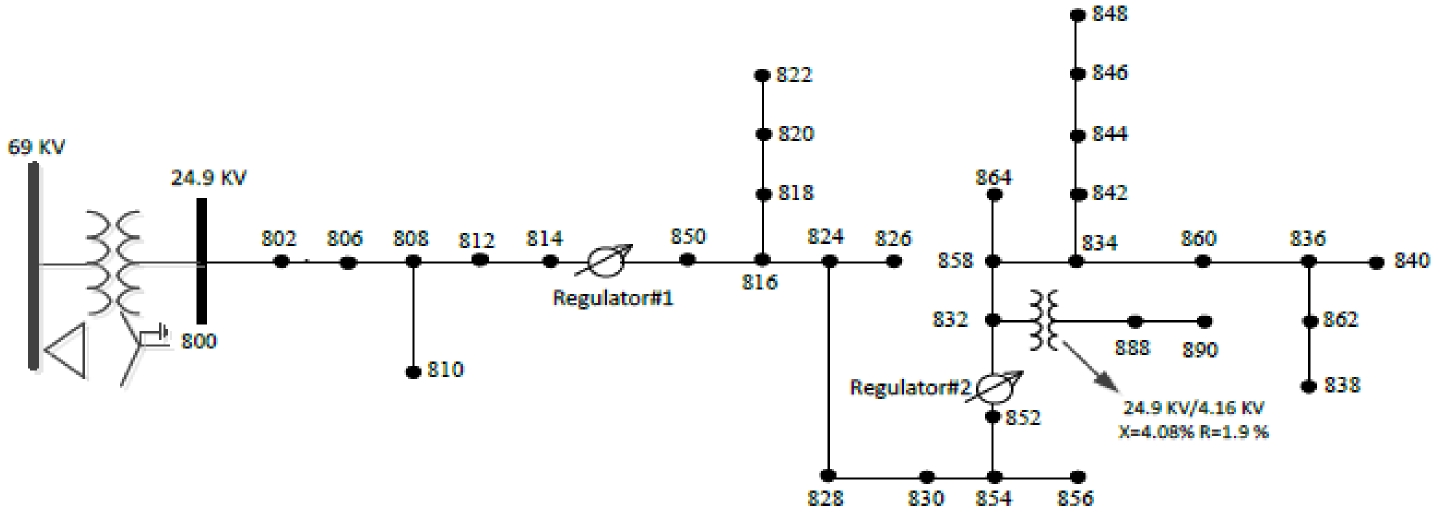
Grid Model – Test Feeder #4 (IEEE 34 Node Feeder – Actual 25 kV & 4.16 kV Circuit in Arizona)

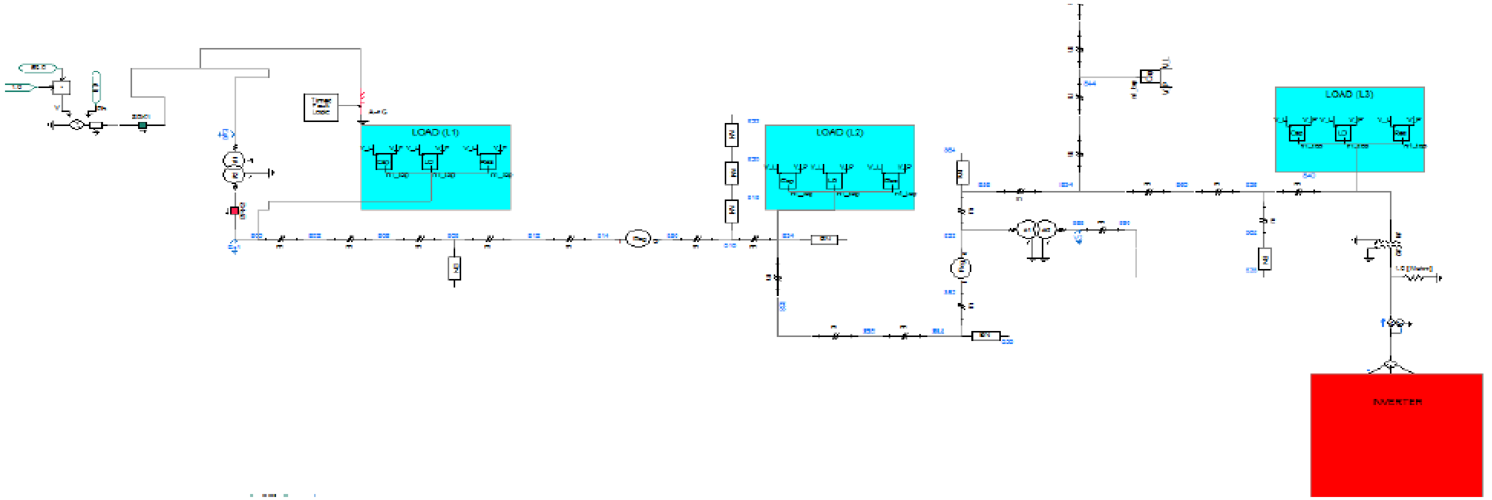


- A very long overhead distribution circuit (36 miles on the main feeder)
- A relatively weak / small 2.5 MVA substation transformer
- Close to the end of the feeder, another in-line step-down transformer feeds 4.16 kV circuit
- Two in-line voltage regulators

Grid Model – Test Feeder #4 (IEEE 34 Node Feeder – Actual 25 kV and 4.16 kV Circuit in Arizona)

Node A	Node B	Length(ft.)	Config.	ID	Phasing	Impedance matrix Z (R +jX) in ohms per mile[9]
800	802	2580	300	500	B A C N	1.3368 1.3343 0.2101 0.5779 0.2130 0.5015 1.3238 1.3569 0.2066 0.4591 1.3294 1.3471
802	806	1730				
806	808	32230				
808	812	37500				
812	814	29730				
888	890	10560				
808	810	5804	303	510	B N	0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 2.7995 1.4855 0.0000 0.0000 0.0000 0.0000
824	826	3030				
854	856	23330				
814	850	10	301	500	B A C N	1.9300 1.4115 0.2327 0.6442 0.2359 0.5691 1.9157 1.4281 0.2288 0.5238 1.9219 1.4209
816	824	10210				
824	828	840				
828	830	20440				
830	854	520				
832	858	4900				
834	860	2020				
834	842	280				
836	840	860				
836	862	280				
842	844	1350				
844	846	3640				
846	848	530				
850	816	310				
852	832	10				
854	852	36830				
860	836	2680				
858	834	5830				
858	864	1620	302	510	A N	2.7995 1.4855 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
816	818	1710				
818	820	48150				
820	822	13740				
862	838	4860	304	510	B N	0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 1.9217 1.4212 0.0000 0.0000 0.0000 0.0000





Load Model

- 3VO scenario is a combination of SLG fault and islanding event
- The loads are tuned to match generation on the feeder with load quality factor of 2.5
  - It is more difficult to detect the islanding condition when the load has a high a high-quality factor

$$Q = \frac{\sqrt{Q_L \times Q_C}}{P_R}$$

Where:
Q= Load's quality factor
Q_L: Inductive power of the load
Q_C: Capacitive power of the load
P_R: Resistive power of the load

IEEE P1547.1 and IEEE Std.929, respectively, recommended islanding test procedure based on load quality factors of 1 and 2.5.

Inverter Model

Five different inverter models

Two Commercial Inverters are able to detect the SLG fault and trip very fast (cannot be used to test the NSV logic)

Inverter 1 , 4 and 5 are used in multiple inverter cases

1. Inverter model #1: 250 kW, three-phase, potential GFOV issue, “blackbox”
2. Inverter model #2: 250 kW, three-phase, high sensitivity to ground faults , “blackbox”
3. Inverter model #3: 1 MW, three-phase, potential GFOV issue, “blackbox”
4. Inverter model #4: 1 MW, power regulated current source inverter, NREL, “generic”
5. Inverter model #5: 500 kW, power regulated voltage source inverter with MPPT, MHRC, “generic”

Commercial Inverters UL-1741 Certified with “blackbox” model

Generic Inverter Models with two different control strategies developed by NREL and MHRC

NSV Protection Scheme

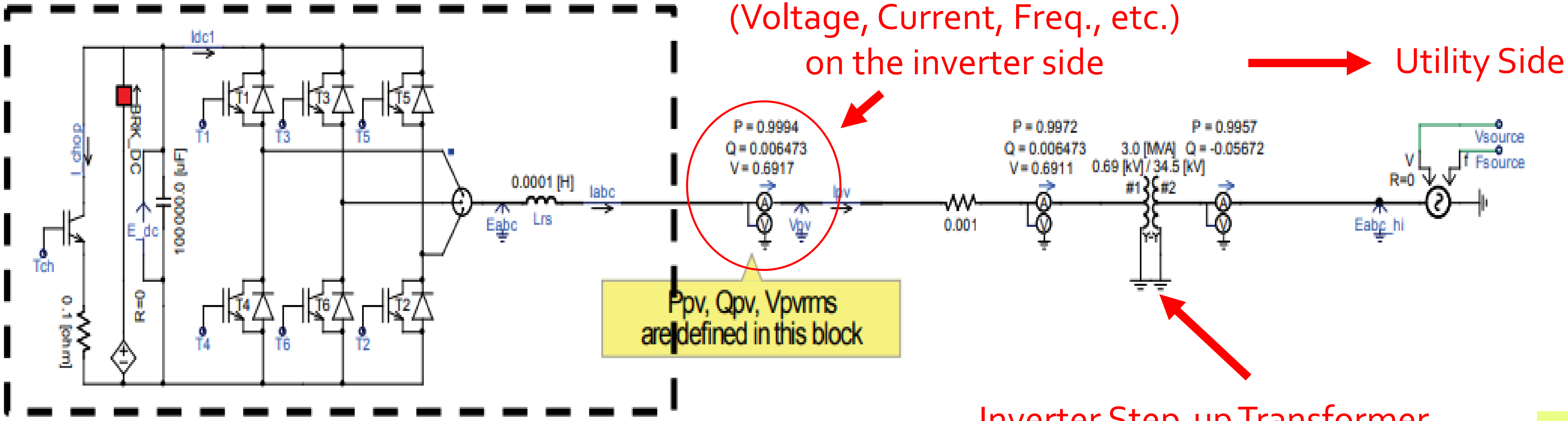
Objectives:

Cost effective

Respond faster

Focus of investigation:

- Detection on the low-voltage side of the substation transformer
- Do not require extensive amounts of additional equipment, material or construction
- Monitor parameters that distinctly identify a potential GFOV condition without being overly subject to over sensitivity (such as nuisance tripping) or under sensitivity (such as failing to detect the onset or presence of GFOV)



NSV Protection Scheme

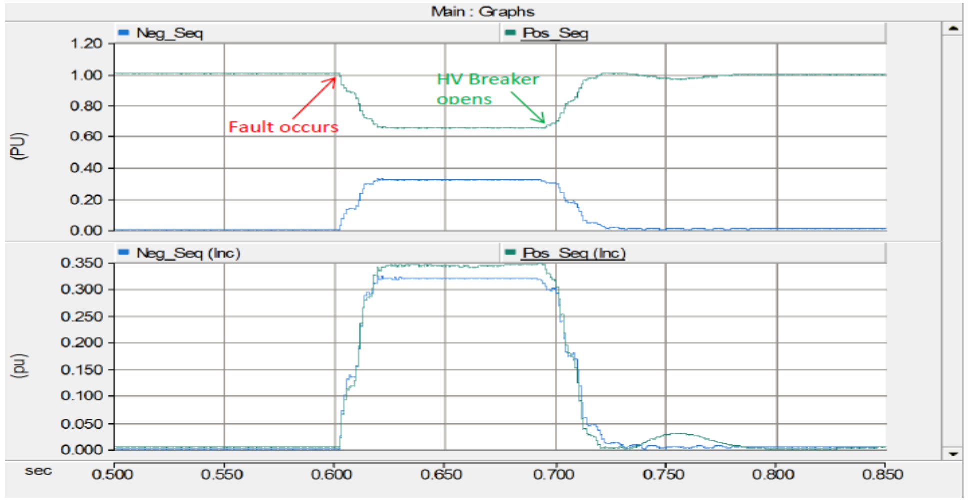
Try these parameters:

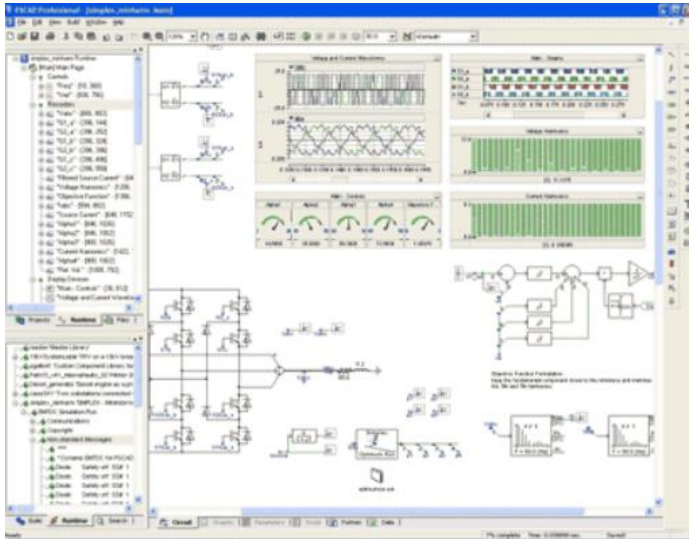
- Voltage imbalance
- Negative sequence current
- Negative sequence directional
- Transient voltage rate of rise
- Many other parameters…

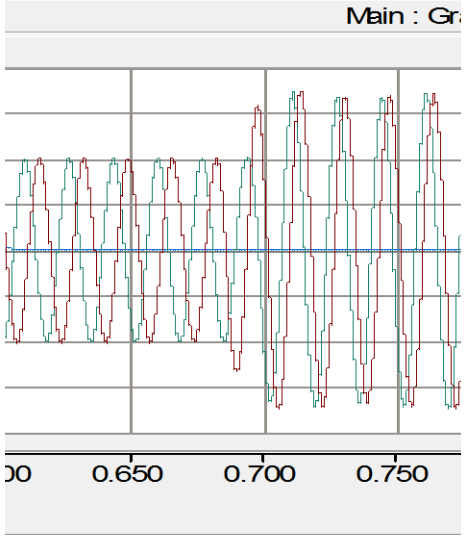
Most effective:

- Negative sequence voltage jump
- Ratio of negative and positive sequence voltages

Pterra modeled and simulated the model utilizing PSCAD EMTC software



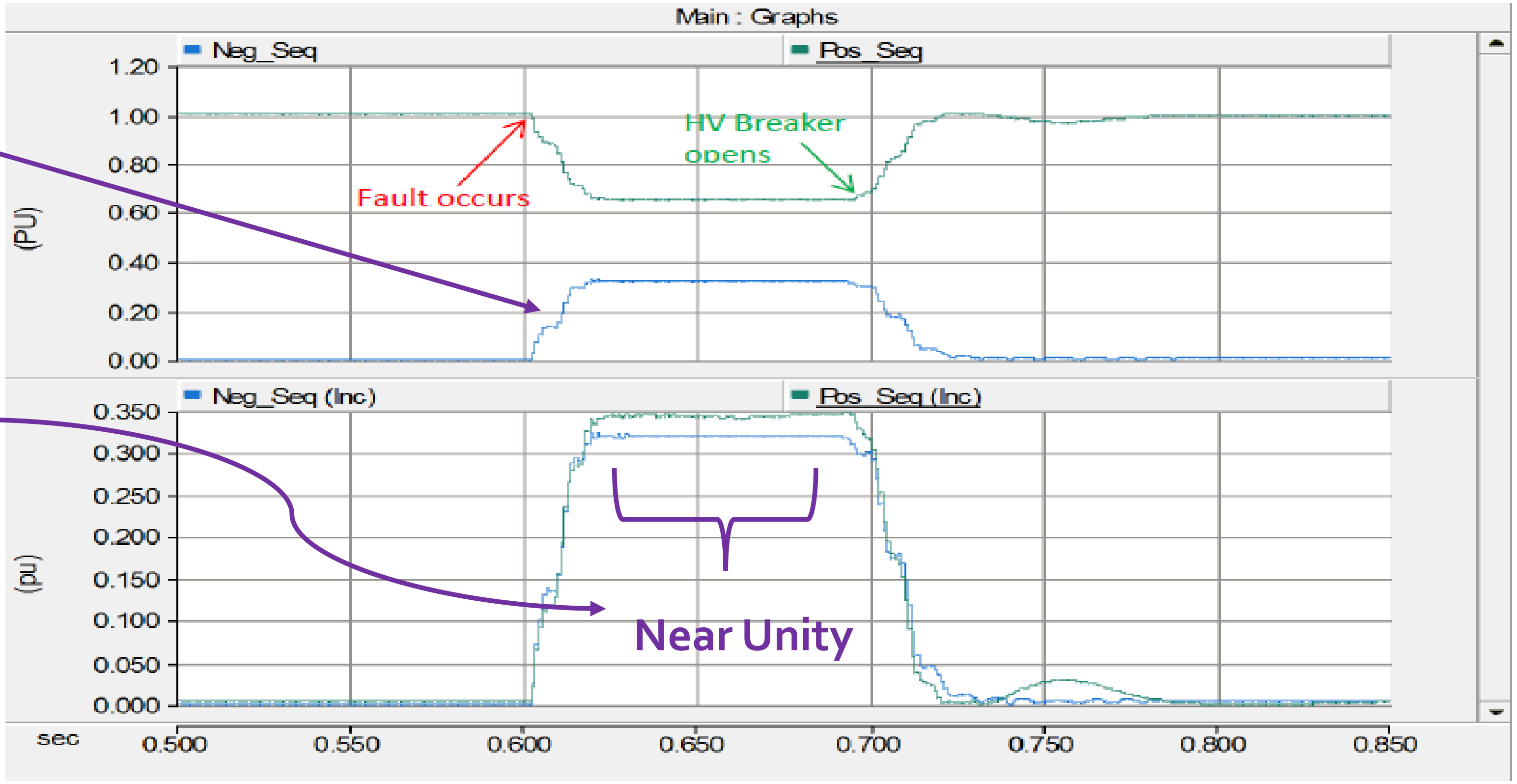




NSV Protection Scheme

General Logic Discussion:

1. Immediately after the SLG fault is applied, the positive sequence voltage drops while the negative sequence voltage rises rapidly.
2. Shortly after the SLG fault occurs, the ratio of incremental negative sequence voltage to incremental positive sequence voltage is near unity.
3. The ratio remains near unity until the HV breaker opens, when the negative sequence shows a sudden decrease.



NSV Protection Scheme

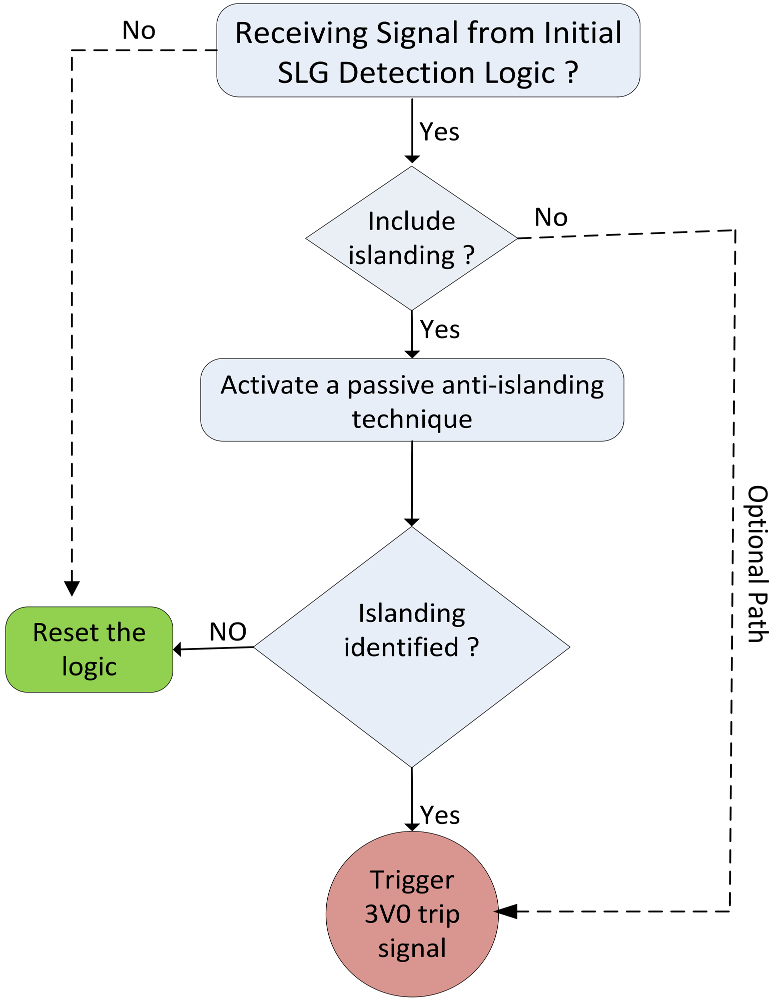
Two Options for completing the scheme after the initial SLG detection logic:

Option 1:

1. Immediately send out trip signal after about 5 cycles (sub-transmission breaker opening time)

Option 2:

1. Activate islanding detection logic
2. If SLG Fault and Islanding are true, then trip the inverter



NSV Simulation

- One Inverter Case without NSV Scheme

Event: Simulations using Inverter #1 or #3 under Single-Line-to-Ground Fault on high-voltage side of Substation transformer, breaker opens in 5 cycles

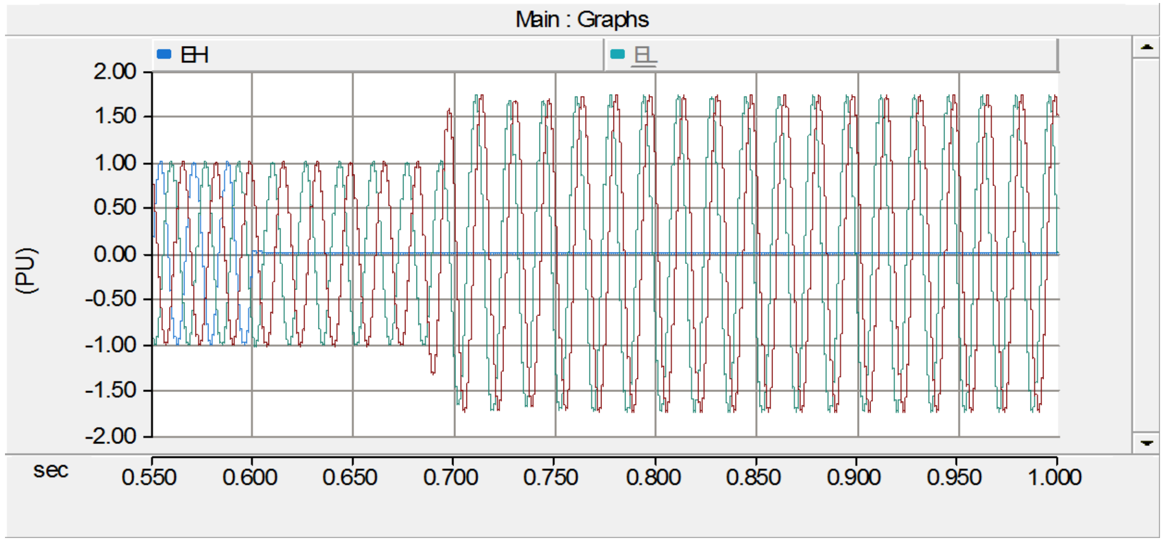
Test Feeder #	Grid SC = 1 kA Weak Grid			Grid SC = 63 kA Stiff Grid		
	Test Case#	Inverter Model	Test Result	Test Case#	Inverter Model	Test Result
1	1	#1	GFOV	9	#1	GFOV
2	2			10		
3	3			11		
4	4			12		
1	5	#3	No GFOV	13	#3	No GFOV
2	6			14		
3	7			15		
4	8			16		

Commercial Inverter#1 fails to detect SLG Fault

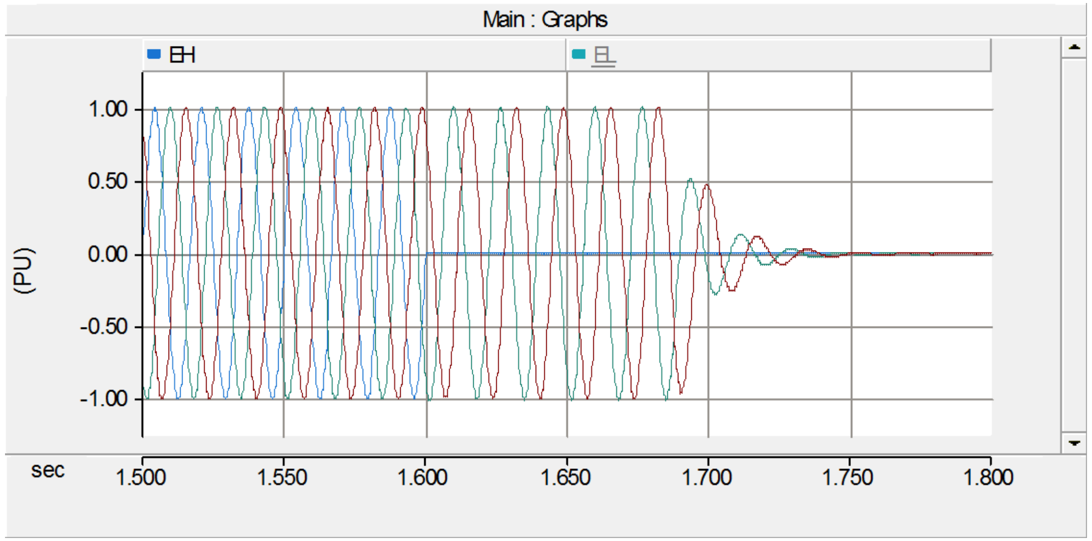
Commercial Inverter#3 is able to detect SLG Fault and trip. Inverter#2 has similar response

NSV Simulation – One Inverter Case without NSV Scheme

Test Case #4: Voltage at Primary Side of Substation Transformer following SLG Fault – Inverter #1, weak grid



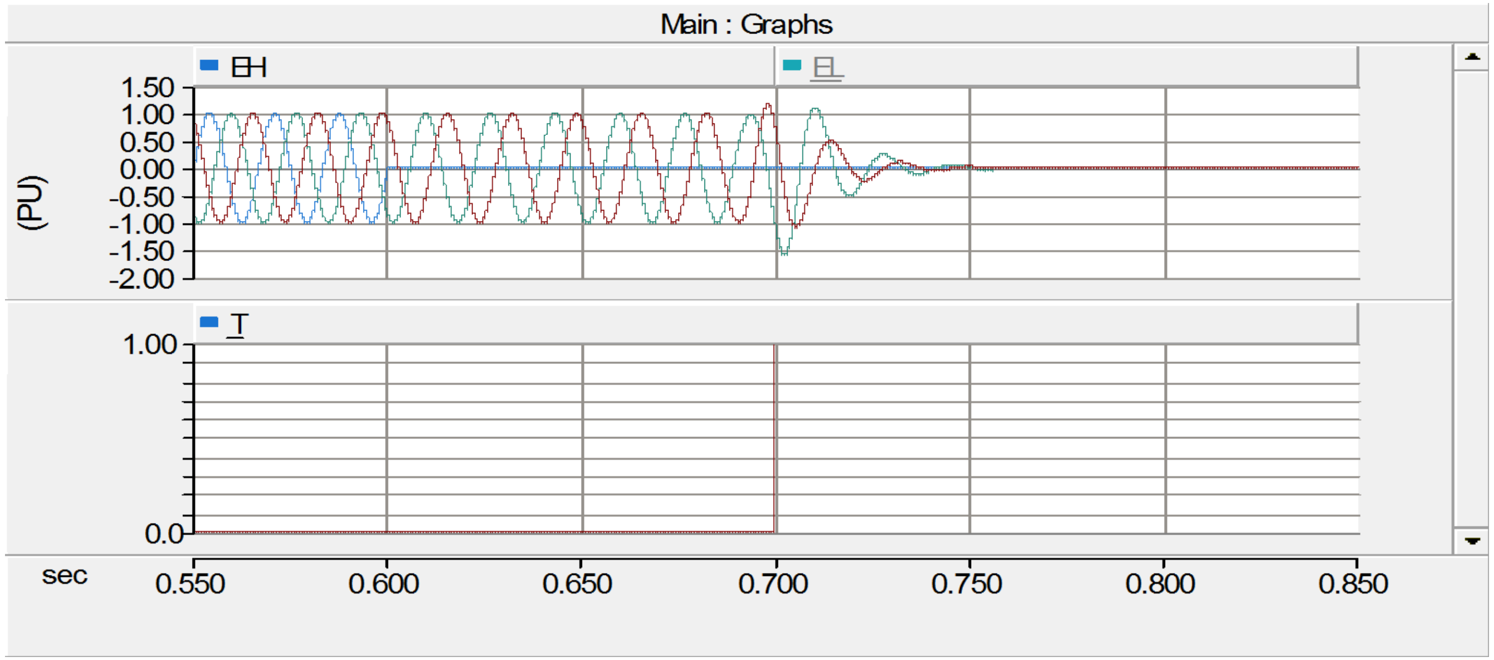
Test Case #8: Voltage at Primary Side of Substation Transformer following SLG Fault – Inverter #3, weak grid



- Inverter#1 is unable to detect the faulted condition and stays online. GFOV is observed on the primary side of the substation transformer (delta side) after the HV breaker opens.
- Inverter #3 is sensitive to the faulted condition. No ground fault overvoltage is observed in test cases with inverter#3

NSV Simulation – One Inverter Case with NSV Scheme

Test Case #4 with NSV Scheme: Voltage at Primary Side of Substation Transformer following SLG Fault – Inverter #1



- At 0.6 s, the SLG fault is applied
- At 0.6833 s, the HV breaker opens
- At 0.7 s, the NSV logic issues a trip signal
- By 0.75 s, voltages on the high side are essentially zero

(*) The logic with islanding detection trip inverter within 4 cycles after the breaker open
(*) The logic without islanding detection can trip inverter just before breaker opens

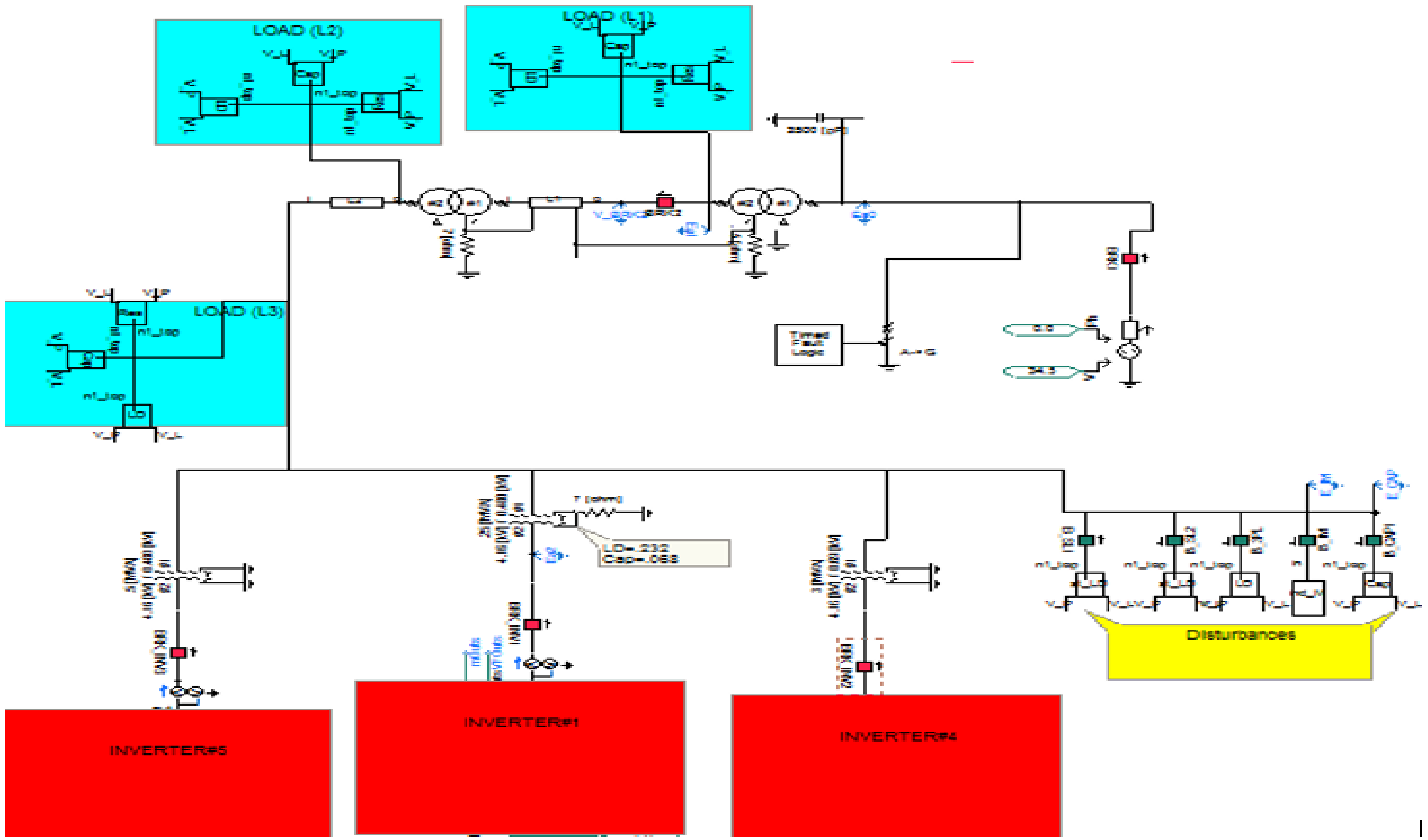
NSV Simulation

- Multiple Inverters Case with/without NSV Scheme

<table>
<tr><th>Test Case#</th><th>Test Feeder #</th><th>Grid SC</th><th>Inverters</th><th>Logic Status</th><th>Test Case#</th><th>Logic Status</th></tr>
<tr><td>17</td><td>1</td><td rowspan="4">1 KA</td><td rowspan="8">#1, #4, & #5</td><td rowspan="8">Monitoring</td><td>25</td><td rowspan="8">Monitoring & Control</td></tr>
<tr><td>18</td><td>2</td><td>26</td></tr>
<tr><td>19</td><td>3</td><td>27</td></tr>
<tr><td>20</td><td>4</td><td>28</td></tr>
<tr><td>21</td><td>1</td><td rowspan="4">63 KA</td><td>29</td></tr>
<tr><td>22</td><td>2</td><td>30</td></tr>
<tr><td>23</td><td>3</td><td>31</td></tr>
<tr><td>24</td><td>4</td><td>32</td></tr>
</table>

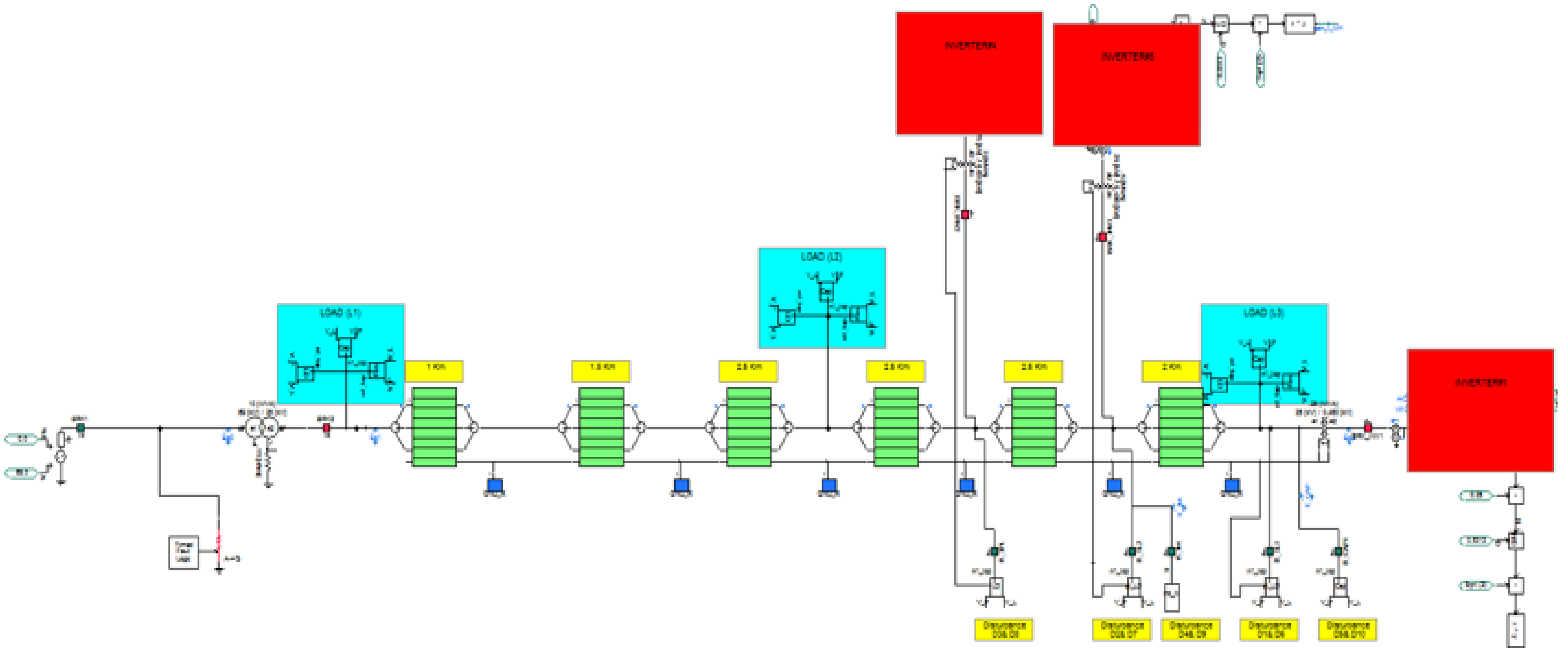
NSV Simulation – Multiple Inverters Case

Top View of the PSCAD Model-Test Case#17 showing location of Inverters in Test Feeder #1



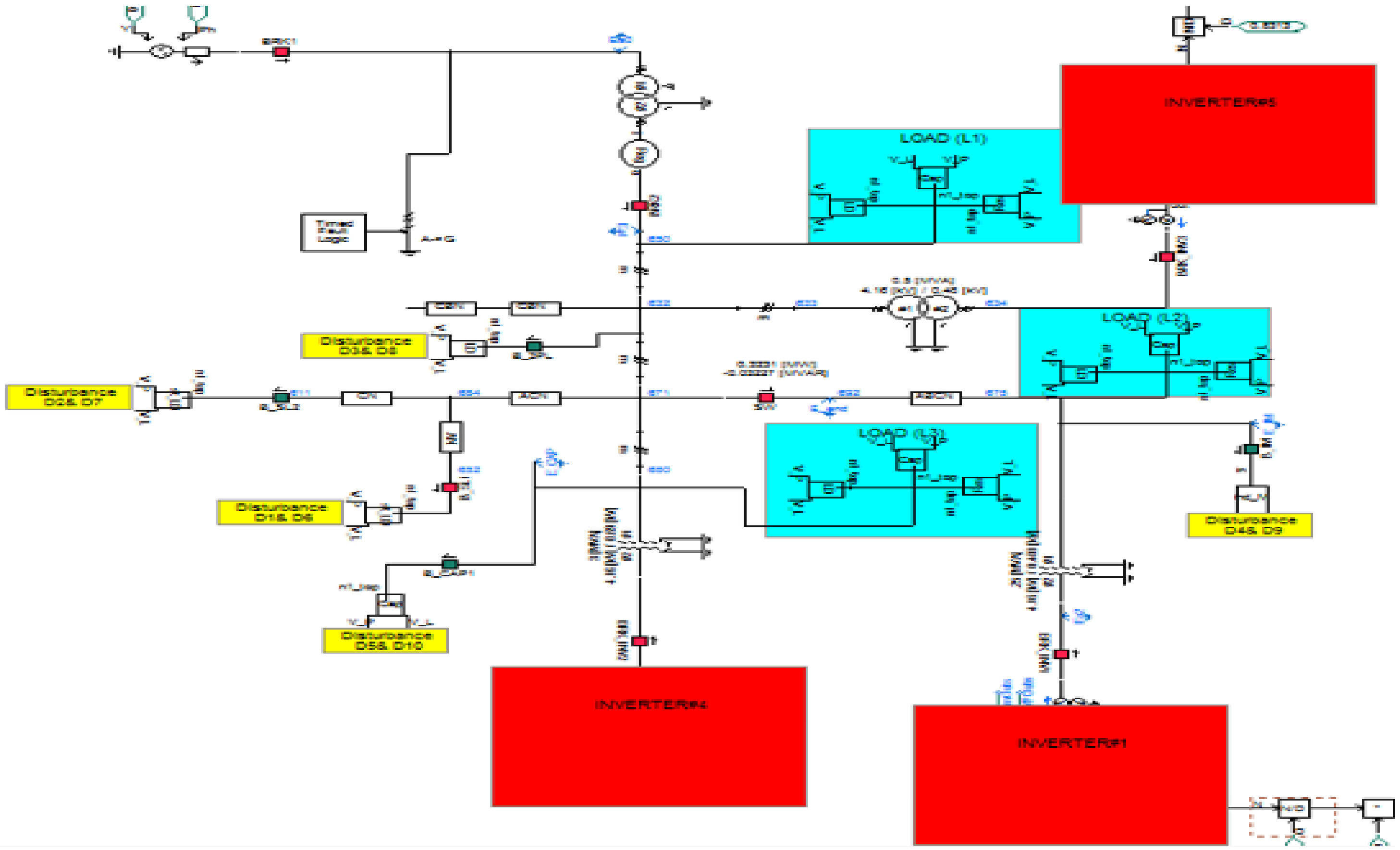
NSV Simulation – Multiple Inverters Case

Top View of the PSCAD Model-Test Case#18 showing location of Inverters in Test Feeder #2



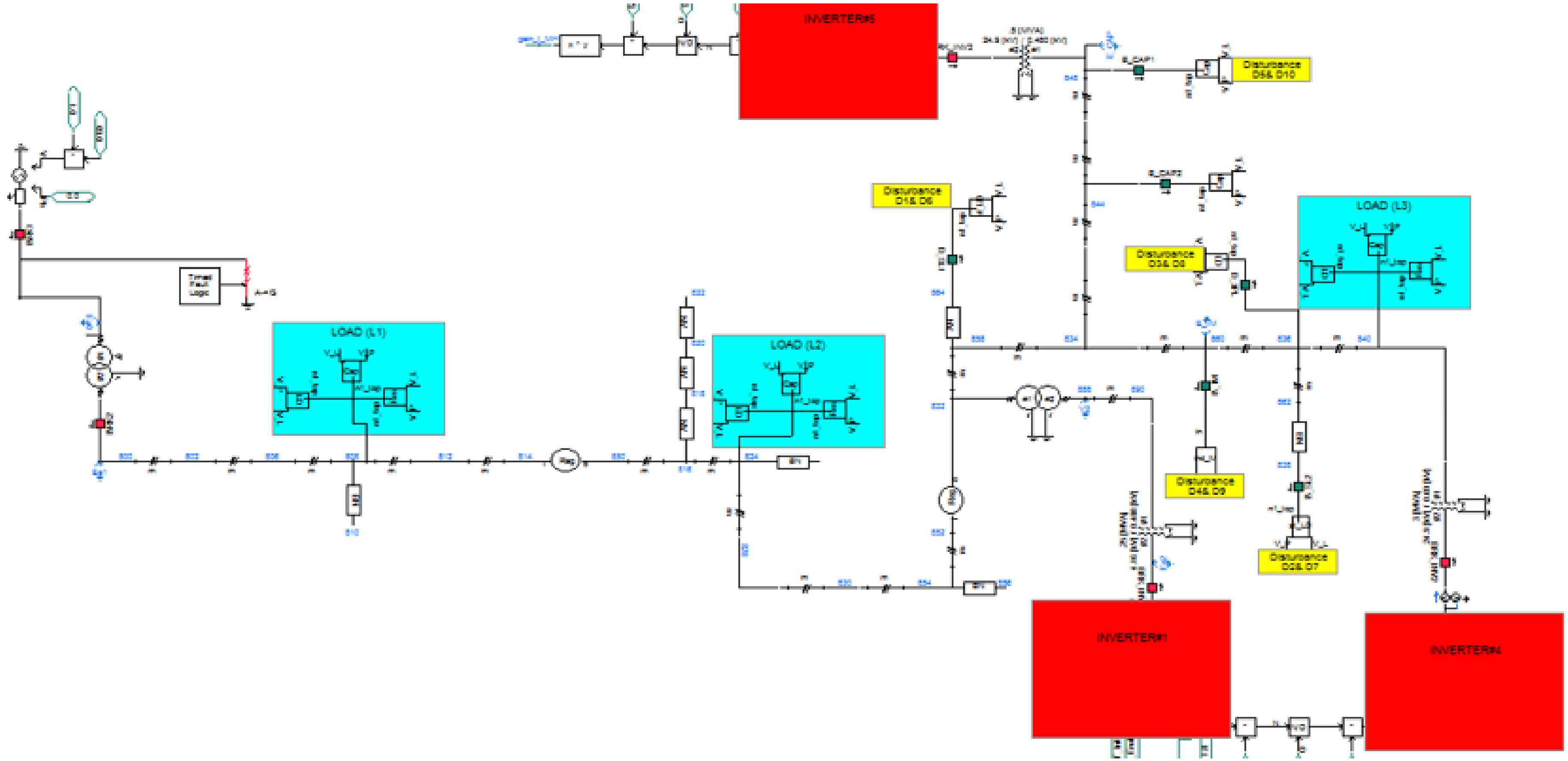
NSV Simulation – Multiple Inverters Case

Top View of the PSCAD Model-Test Case#19 showing location of Inverters in Test Feeder #3



NSV Simulation – Multiple Inverters Case

Top View of the PSCAD Model-Test Case#20 showing location of Inverters in Test Feeder #4



NSV Simulation

- Additional Switching Disturbances Prior to the SLG Fault

Switching Disturbance#	Description	Time Applied (s)
SD#1	400 kW single phase load with unity power factor (D1) is switched in	.4
SD#2	400 kW single phase load with a power factor of .8 lag (D2) is switched in	.5
SD#3	500 kW three phase load with a power factor of .85 lag (D3) is switched in	.6
SD#4	500 HP/460 V motor load (D4) is switched in	.7
SD#5	450 kVAR cap bank (D5) is switched in	.8
SD#6	400 kW single phase load with unity power factor (D1) is switched out	.9
SD#7	400 kW single phase load with a power factor of .8 lag (D2) is switched out	1
SD#8	500 kW three phase load with power factor of .85 lag (D3) is switched out	1.1
SD#9	500 HP/460 V motor load (D4) is switched out	1.2
SD#10	450 kVAR cap bank (D5) is switched out	1.3

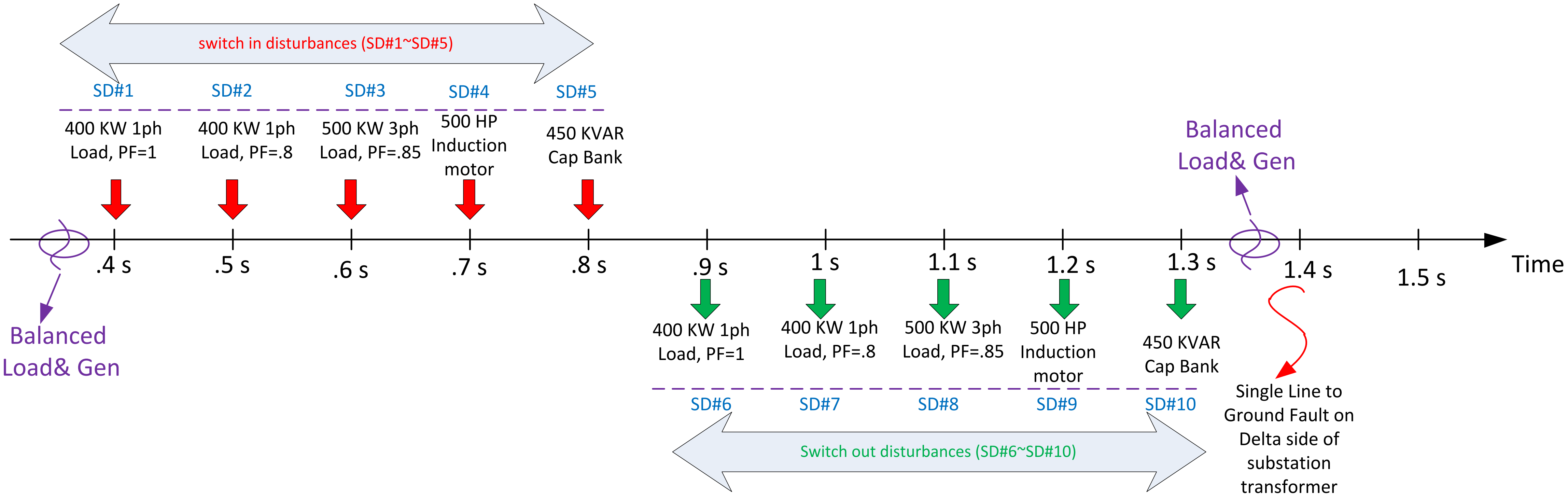
→ Gen = Load

Energization

De-energization

→ Gen = Load

NSV Simulation – Additional Switching Disturbances

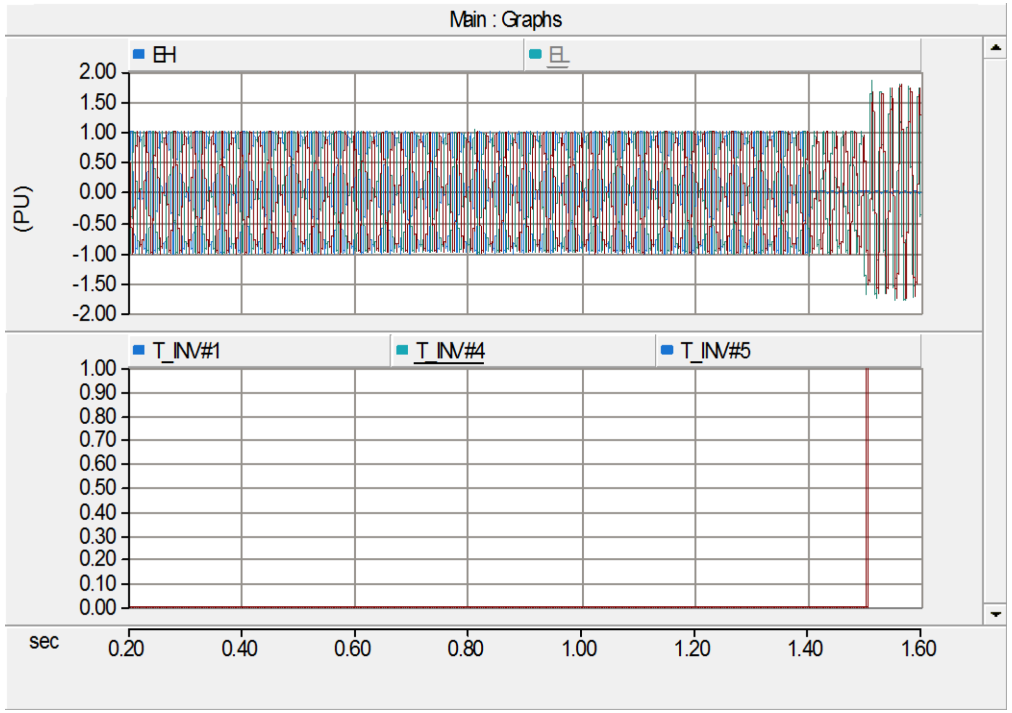


Note:

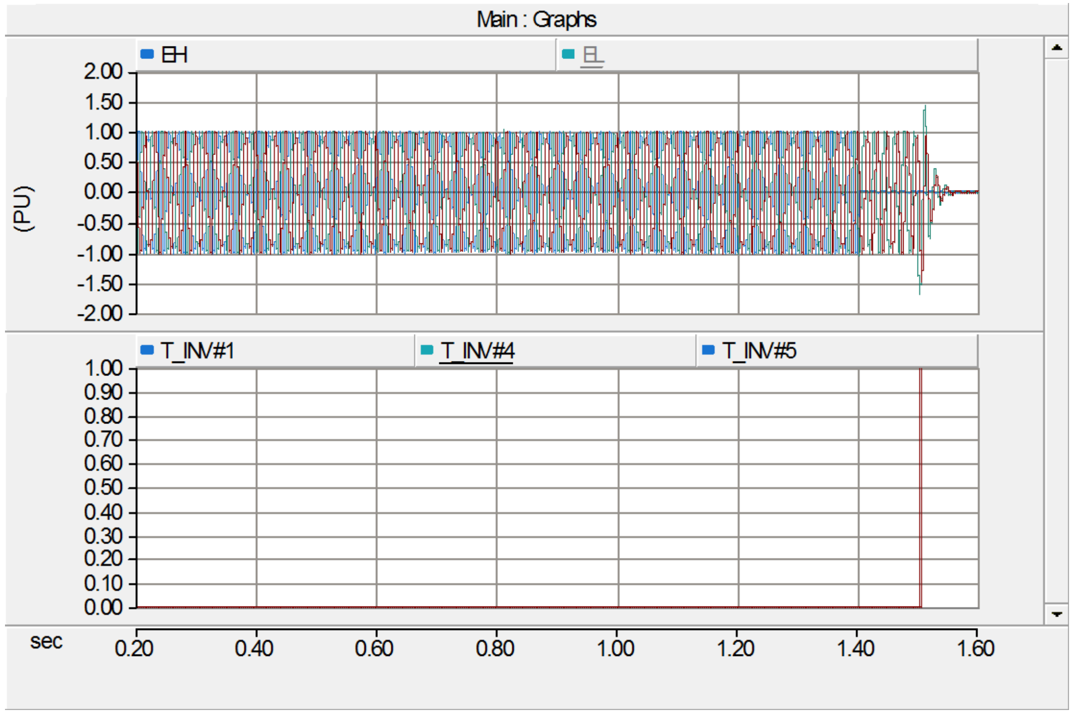
- The distributed loads, L1, L2 and L3, in each test case are tuned such that current passing from the upstream circuit breaker would be close to zero before the occurrence of first disturbance and shortly after the last disturbance.

NSV Simulation

Voltage at Primary Side of Substation Transformer (top) and the Logic Trip Signals (bottom)- Test Case#18



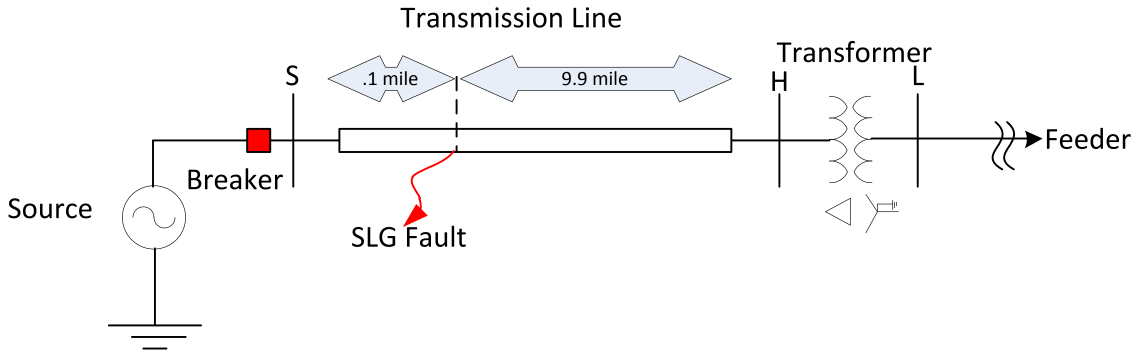
Voltage at Primary Side of Substation Transformer (top) and the Logic Trip Signals (bottom)- Test Case#26



- The NSV is not triggered by the miscellaneous switching events and is able to recognize the potential GFOV and trip the associated PV in a few cycles.

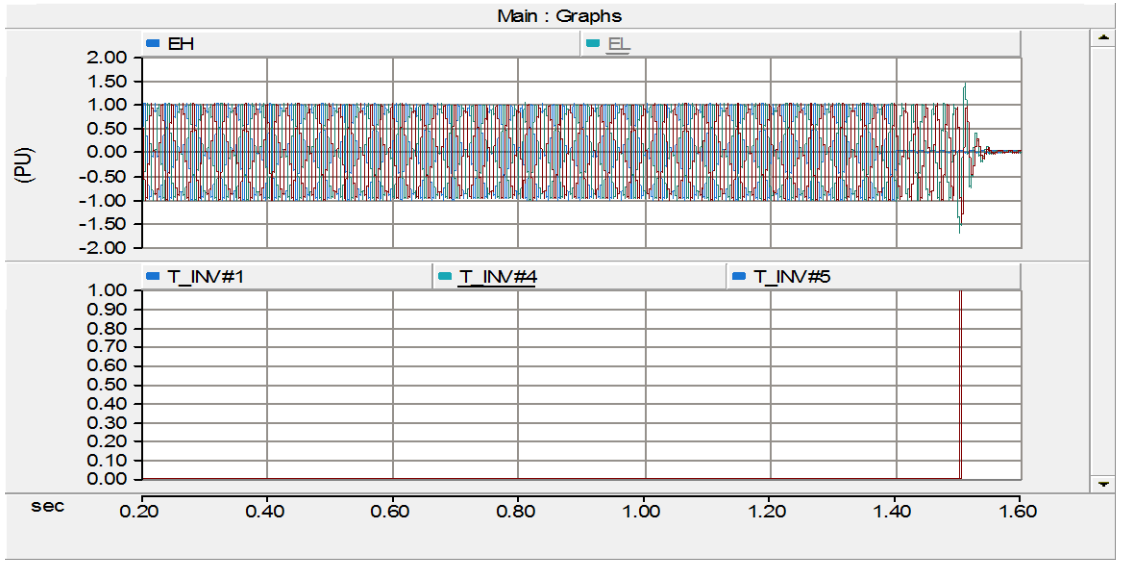
NSV Simulation

- Sensitivity Tests with Transmission Line Model
  - In reality, a sub-transmission line connecting the substation transformer high side with the HV substation is present and can be several miles long.
  - The fault may occur anywhere along this line with the same potential for GFOV.
  - To evaluate the effect of the sub-transmission line on the NSV protection scheme, a 10-mile long overhead line is added to the model for Test Cases #25 through #32.

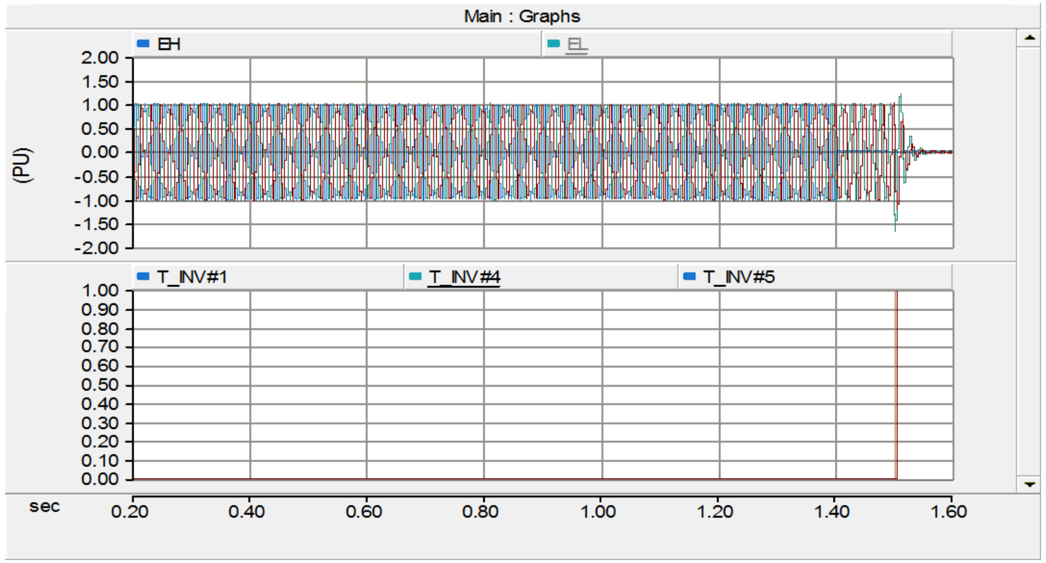


NSV Simulation – Sensitivity Tests

Voltage at Primary Side of Substation Transformer (top) and the Logic Trip Signals (bottom)- Test Case #26 without Transmission Line



Voltage at Primary Side of Substation Transformer (top) and the Logic Trip Signals (bottom)- Test Case #26 with Transmission Line



- The response of the NSV scheme is nearly the same as the test case with no transmission line.
- The NSV's logic is able to avoid GFOV without causing nuisance tripping even if the fault is far away from the substation transformer.

Part-1 Conclusion and Future Work

- The research findings confirm that the need for the expensive PTs and 0.5-1 year construction time may be avoided with the NSV protection scheme with a detailed design of the NSV implementation at individual PV inverters

- The concept would need to be confirmed with a detailed design of the NSV implementation at either the substation or at individual PV inverters. Testing the scheme with programmed inverters through a hardware-in-the-loop (HIL) simulation is a possible next step to further evaluate the NSV scheme.

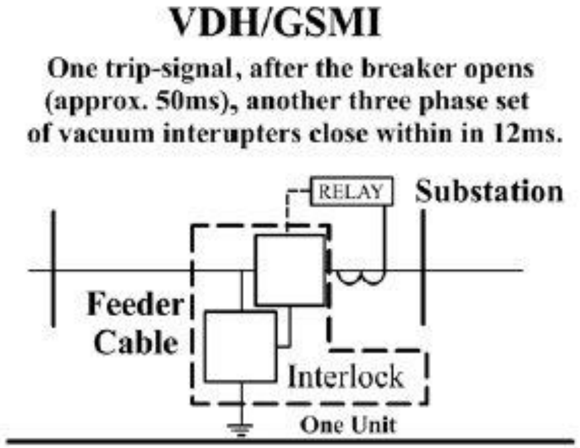
- Field tests can be conducted with devices that support the NSV protection scheme to verify that the performance matches the simulations.

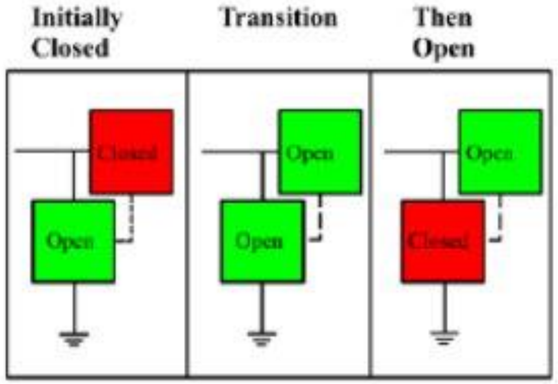
PART 2 – Additional Guidance to PV Developers and Utilities and Future Design Options

A Hardware Alternative for 34.5 kV Systems: Grounding Breaker

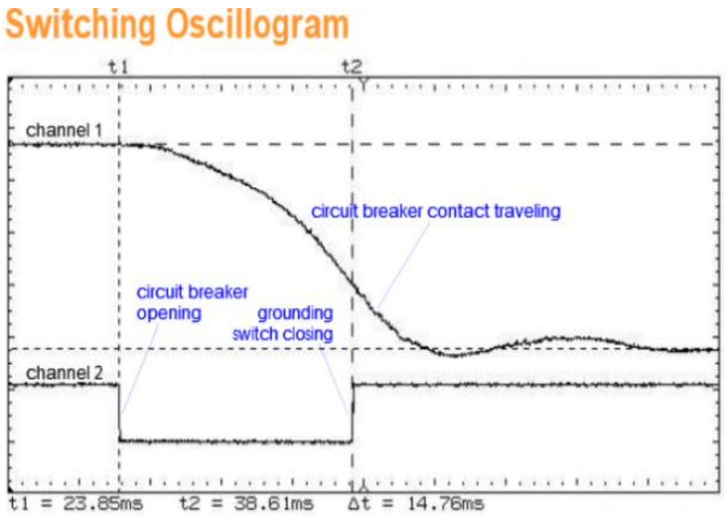
- A 34.5 kV sub-transmission system may serve several distribution substations, and a 3V0 scheme may be required for each of the connected distribution substations.
- 3V0 scheme will take at least 5 or more cycles before it can detect the GFOV condition and trip the low-side breaker
- The 34.5 kV breaker can be replaced with a so-called “grounding breaker”, which is a combined circuit breaker and high-speed, mechanically-interlocked grounding switch.
- During a disturbance, such as a fault, where the breaker trips, the attached switch also grounds the line, providing a ground path.
- The grounding is accomplished in 12 to 16 milliseconds (less than one cycle) after the breaker opens, fast enough to avoid a prolonged GFOV state.

NSV Simulation – Grounding Breaker





VDH/GSMI States



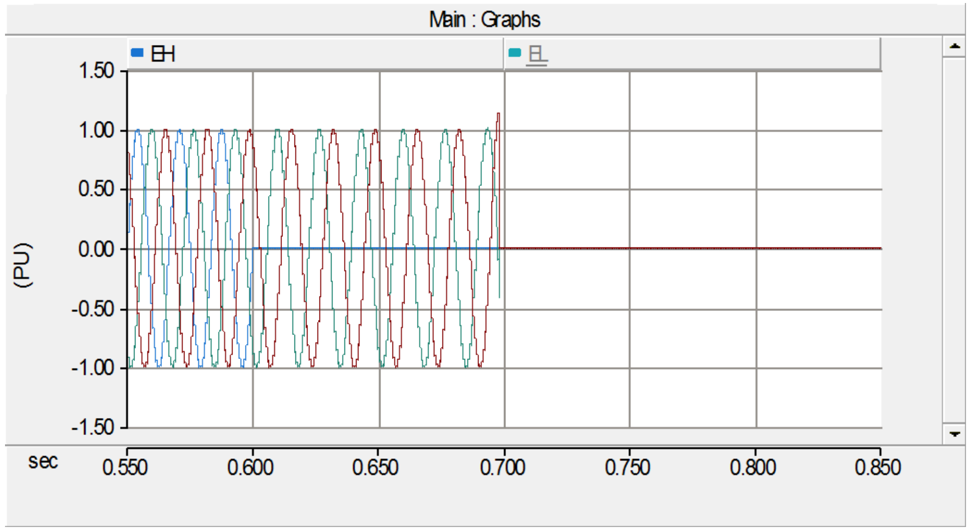
Advantages:

1. Less costly for situations where there are multiple distribution substations connected to the same 34.5 kV sub-transmission line.
2. Clear GFOV faster, within 12-16 milliseconds after the breaker opens, compared to the 3V0 method which may take 5 cycles or more to remove the GFOV.
3. More reliable as the grounding breaker is triggered by a single fault protection relay while each 3V0 scheme independently relies on its own relaying to trigger and trip the associated low-side breakers. If any one of the 3V0 schemes fails to perform then the GFOV may occur..

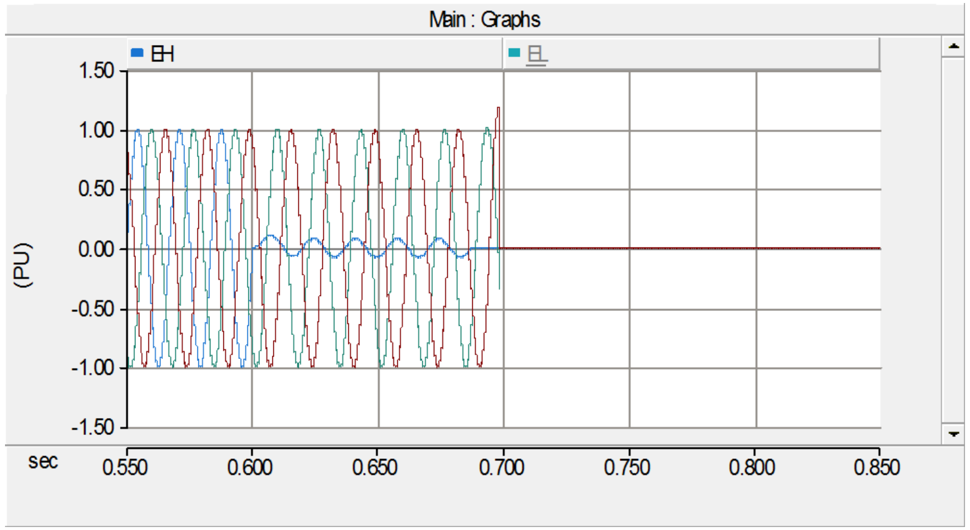
NSV Simulation – Grounding Breaker

Scenario	Base Case	Modification of the Base case	GFOV at Primary Side of Substation Transformer w/o Grounding Breaker?	GFOV at Primary Side of Substation Transformer with Grounding Breaker?
4-2-1	Test case #4	Replace circuit breaker with grounding breaker	Yes	NO
4-2-3	Test case #12	Replace circuit breaker with grounding breaker	Yes	NO

Voltage at Primary Side of Substation Transformer –Modified Case Scenario 4-2-1



Voltage at Primary Side of Substation Transformer –Modified Case Scenario 4-2-3



Additional Guidance to PV Developers and Utilities

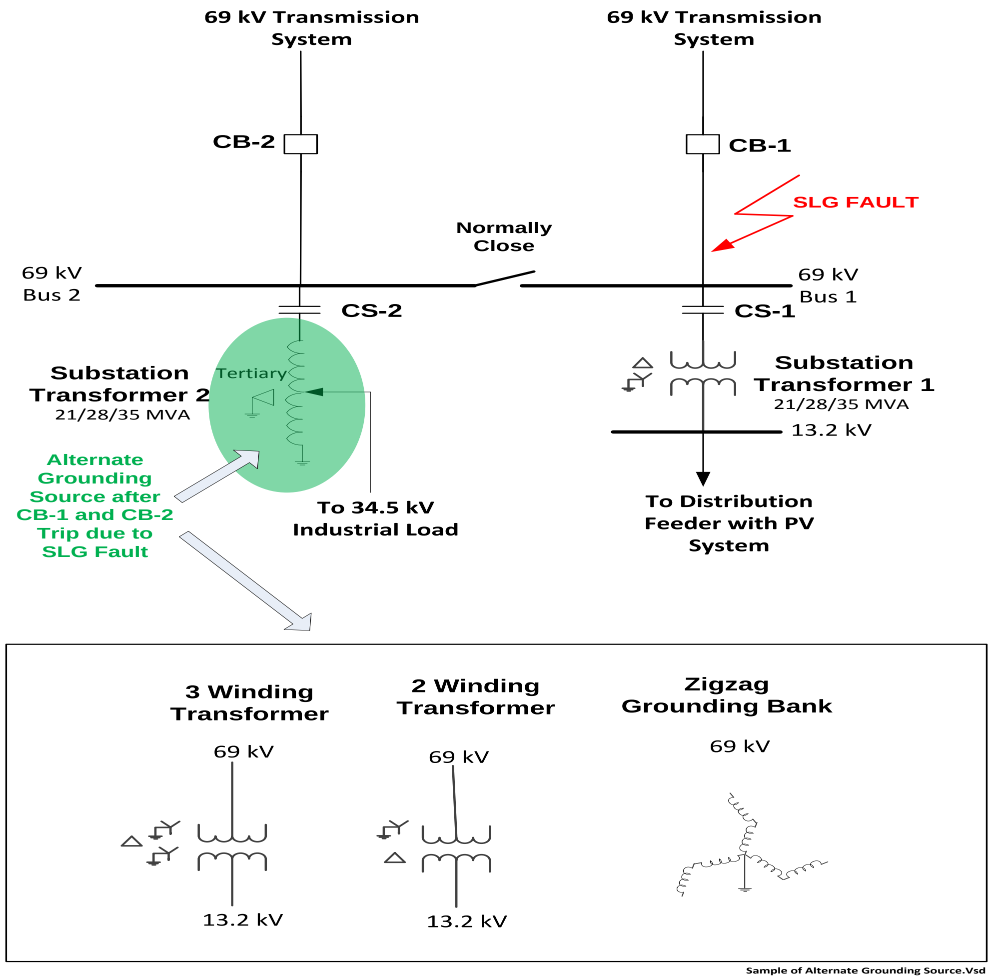
- Objective
  - How to review an existing system configuration for potential GFOV conditions.
  - What option is available when upgrading a sub-transmission/distribution system to ensure that there is no risk of GFOV.
- Review of Existing System Configuration
  - Check for presence of alternate grounding sources.
  - Analyze load to DER ratios for all possible islands.
  - Where applicable, evaluate capabilities of surge arresters on the high-voltage side of possible islands to mitigate GFOV.

Additional Guidance to PV Developers and Utilities

- Possible Alternate Grounding Sources
  - ➢ A substation transformer with any of the following connections, even if there are no PVs connected on the low-voltage side of the transformer.
    - Two-winding transformer with wye-grounded connection on the sub-transmission side and delta on the low voltage side
    - A three-winding transformer with delta tertiary and Y grounded primary and secondary
    - Autotransformer with delta tertiary
  - ➢ Grounding bank with a zigzag transformer.
  - ➢ Other transformer configurations.
- Location of Alternate Grounding Sources
  - ➢ The alternate grounding source needs to be located downstream of the HV breaker.

Additional Guidance to PV Developers and Utilities

- Example of Alternate Grounding Sources



Additional Guidance to PV Developers and Utilities

- Load to DER Ratios
  - According to ANSI/IEEE C62.92, the GFOV for an effectively-grounded system is to be limited to 138%.
  - When PV/load ratio is less than 65%, the maximum GFOV is 1.38 times a pre-fault voltage of 1.0 PU (Phase I Study with assumptions).
  - Concerns
    - Even above 65% PV/load ratio, the likelihood of GFOV is limited by the fact that certain types of inverters are able to recognize the islanded condition and trip offline
    - Since load level is constantly changing on the feeder, the question is: "How to measure the load?"

Additional Guidance to PV Developers and Utilities

- Surge Arresters Connected to the High-voltage side of the Substation Transformer
  - For a 34.5 kV sub-transmission system, 22 KV maximum continuous operating voltage (MCOV) and 24.4 KV MCOV surge arresters (these are rated approximately 10% and 20% above nominal voltage, respectively) can keep the GFOV within 1.38 PU for up to 15 seconds for a PV/load ratio of 105% (Phase I Study).
  - However, it is not clear how quickly and effectively surge arresters can reduce and continuously prevent a GFOV event.
  - During a TOV event of a magnitude as to cause the arrester to conduct to ground, the arrester appears as a nonlinear load to the system, which would introduce sufficient imbalance to an islanded system that will activate anti-islanding protection in individual PV inverters and trip them.

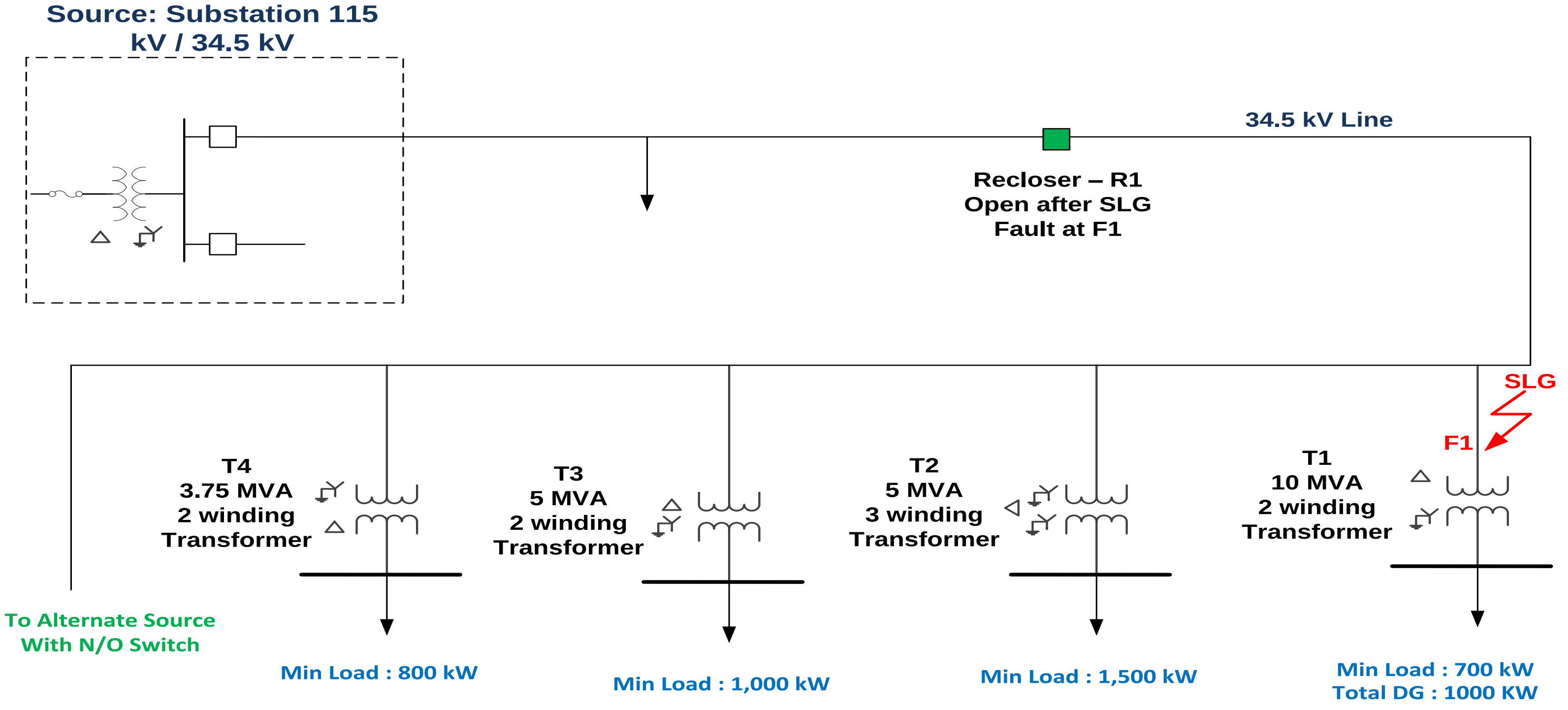
Additional Guidance to PV Developers and Utilities

- Example of Reviewing Existing System Configuration

34.5 kV System showing 34.5 kV Line feeding four 34.5 kV distribution substations

Scenario:
1) SLG Fault at F1 causing recloser R-1 to open/trip
2) DG fed by transformer T1 lost its grounding source from the Source (115/34.5 kV Substation). The island is formed with DG and Transformer T1 through T4 isolated from the Source
3) Utility concerns about GFOV on the isolated 34.5 kV system

Facts:
1) Transformer T2 and T4 can provide alternate grounding source
2) Total DG on the Island = 1000 kW (Fed from transformer T1)
3) Total minimum load on the Island = 4,000 kW
4) Total DG/Minimum Load = 25%



Additional Guidance to PV Developers and Utilities

- Future Design Option

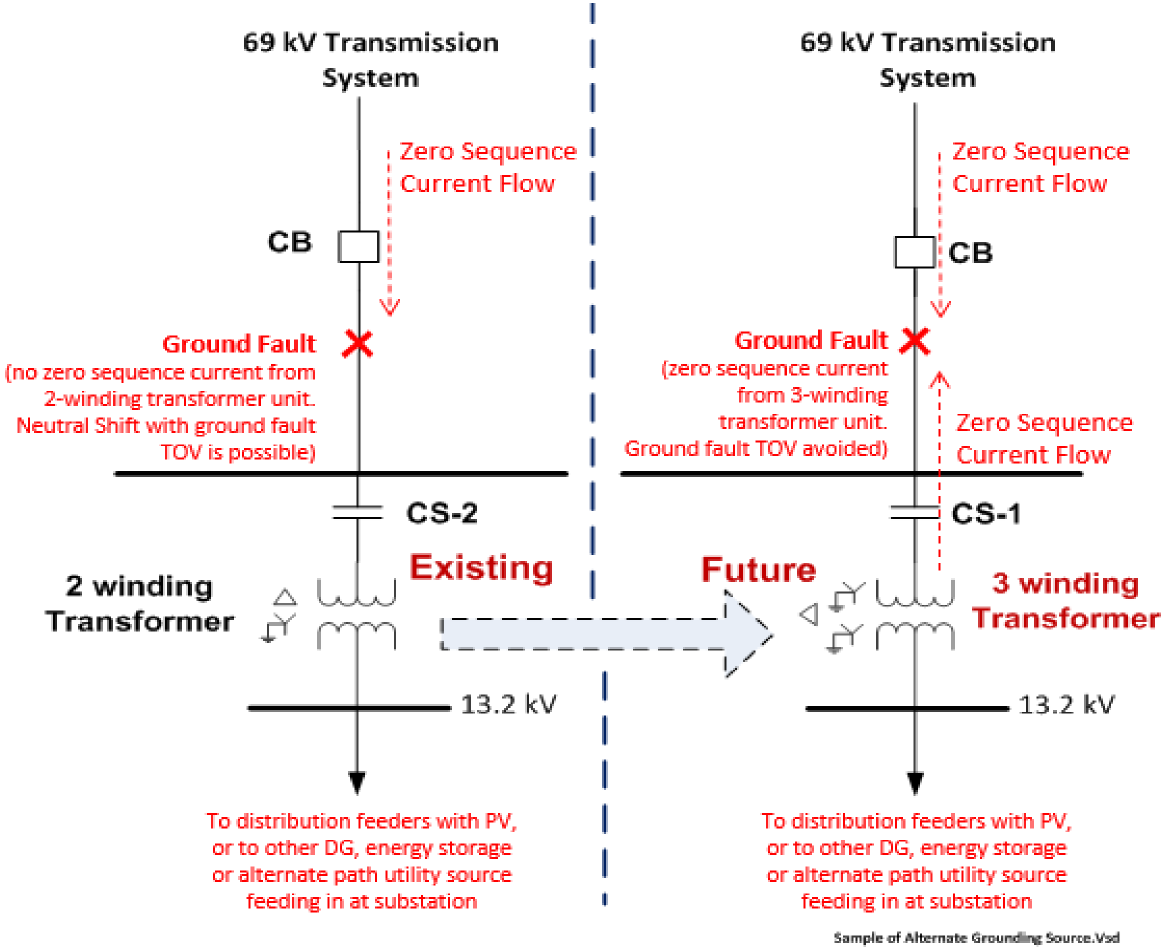
  - A three-winding transformer connected Ygrounded on both the primary and secondary and delta on the tertiary is an option that avoids the issue of GFOV

- Important Technical Aspects

  - Ground Fault TOV Mitigation
  - Ground Fault Current Detection

Additional Guidance to PV Developers and Utilities

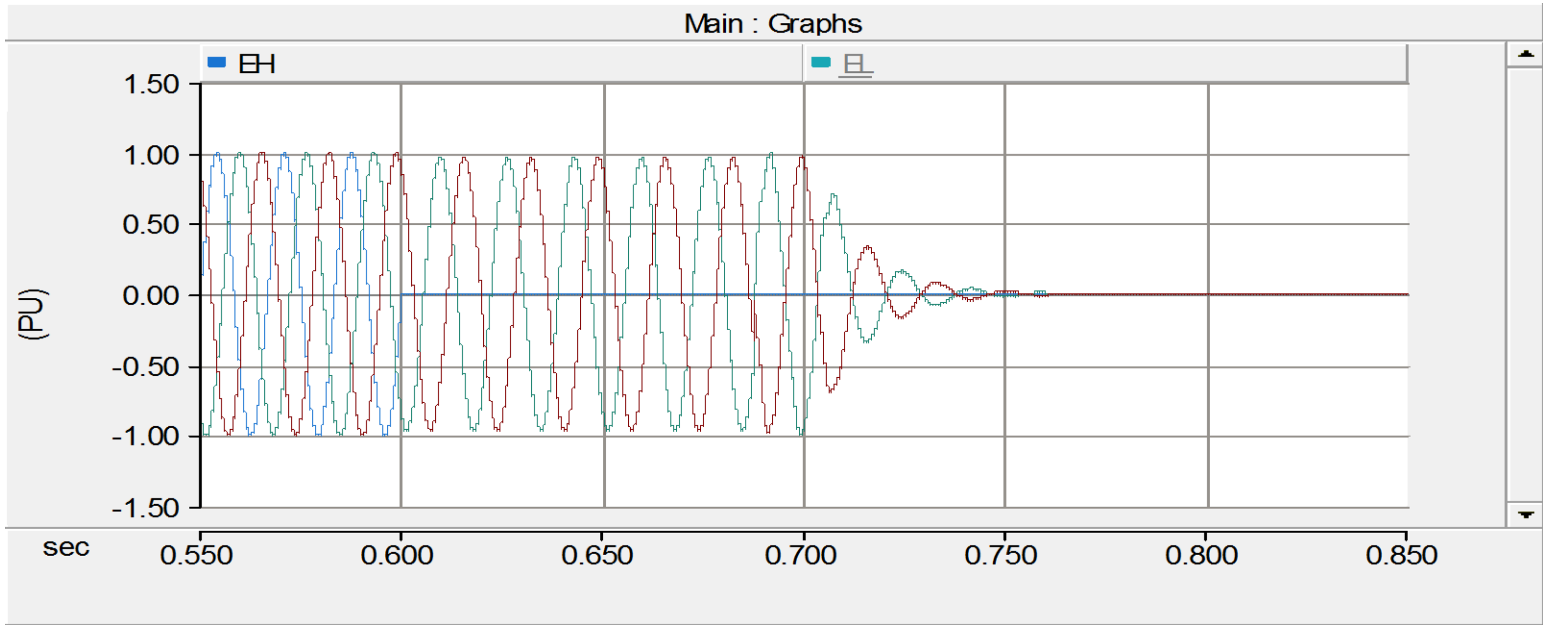
- Future Design Option



Additional Guidance to PV Developers and Utilities

- Future Design Option

The response of voltages on the primary side when using a 3 winding YG/YG/Δ transformer



Conclusions

- In searching for an alternative to the 3V0 protection scheme, the focus of investigation was on protection schemes which feature
  - Detection from on low-voltage side of the distribution substation transformer. This is to avoid the main cost component of the 3V0 scheme which come from the need for potential transformers and monitoring on the high side of the substation transformer.
  - Do not require extensive amounts of additional equipment, material or construction.
  - Monitor parameters that distinctly identify a potential GFOV condition without being subject to over sensitivity (such as nuisance tripping) or under sensitivity (such as failing to detect the onset or presence of GFOV).

Conclusions

- In monitoring voltages on the low-side of the substation transformer, the need for the expensive PTs and 0.5-1 year construction time may be avoided with the NSV protection scheme. However, the concept would need to be confirmed with a detailed design of the NSV implementation at either the substation or at individual PV inverters. Testing the scheme with programmed inverters through a hardware-in-the-loop (HIL) simulation is a possible next step to further evaluate the NSV scheme.

Conclusions

- For the specific case of a 34.5 kV sub-transmission system which serves several distribution substations, the researchers identified a hardware alternative to the 3V0 protection scheme.
  - ➢The 34.5 kV breaker located at the high voltage substation can be replaced with a “grounding breaker”.
  - ➢Benefits of using the grounding breaker compared to the 3V0 protection scheme are
    - Less costly for situations where there are multiple distribution substations connected to the same 34.5 kV sub-transmission line.
    - More reliable as the grounding breaker is triggered by a single fault protection relay while each 3V0 scheme independently relies on its own relaying to trigger and trip the associated low-side breakers. If any one of the 3V0 schemes fails to perform then the GFOV may occur.
    - Clears GFOV faster, within 12-16 milliseconds after the breaker opens, compared to the 3V0 method which may take 5 cycles or more to de-energize the GFOV.

Conclusions

- The following are supplementary work products developed during the course of the study and are made available for the use and reference of New York utilities.
  - Developed a PSCAD inverter control model that represented a modern inverter which had control strategies and features that can be selected and modified by the researcher
  - Steps of reviewing the existing system configuration to establish whether the potential GFOV issue actually exists
    - Check for presence of alternate grounding sources.
    - Analyze PV-to-load ratios.
    - Consider the impact of surge arresters.

Conclusions

- For future substation design and for transformer replacements at existing substations, a three-winding transformer connected Ygrounded on both the primary and secondary and delta on the tertiary is a design option that avoids the issue of GFOV.

  - The advantages of 3-winding transformers

    - When the upstream breaker trips or opens, the upstream side will still have a grounding source, thus the GFOV issue does not arise.

Questions?

THANK YOU!