August 9th, 2021

SOUTHERN CALIFORNIA EDISON

Fast Curve Protection Philosophy Review

Revision 0

PROJECT NUMBER:
163498
PROJECT CONTACT:
[redacted]
EMAIL:
[redacted]
PHONE:
[redacted]

FAST CURVE PHILOSOPHY REVIEW

PREPARED FOR:
SOUTHERN CALIFORNIA EDISON

PREPARED BY:
[redacted]

REVISION HISTORY						
REV.	ISSUE DATE	ISSUED FOR	PREP BY	CHKD BY	APPD BY	NOTES
A	7/10/2020	Prelim	[redacted]			Issued for SCE review and comment
B	8/31/2020	Appvl				Issued for approval
C	9/11/2020	Impl				Revised based on comments from SCE
D	6/21/2021	Impl				Revised based on comments from SCE
0	8/09/2021	Impl				Revised based on comments from SCE

"Issued For" Definitions:

- "Prelim" means this document is issued for preliminary review, not for implementation
- "Appvl" means this document is issued for review and approval, not for implementation
- "Impl" means this document is issued for implementation
- "Record" means this document is issued after project completion for project file

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Introduction

Wildfires have been a growing concern across the United States and especially in the state of California. Electric utilities have been implementing fire mitigation strategies to combat growing wildfire exposure zones due to the potential of overhead lines and other infrastructure coming into contact with vegetation. Southern California Edison (SCE) has implemented a fast curve protection strategy to speed up fault clearing times to mitigate fire risk. This document is a review of SCE's present fast curve philosophy and contains recommendations to the philosophy which may provide greater reliability and provide greater circuit coverage. A total of 15 circuits were analyzed using the present philosophy and reanalyzed using the revised philosophy to illustrate potential protection improvements. The same 15 circuits were modeled in MATLAB/Simulink to be studied for the effects of AC motor stalling caused by low voltage events due to faults on adjacent circuits or the subtransmission system. In addition to reviewing SCE's protection philosophy, a brief overview of 2 other electric utility fire protection philosophies are provided for SCE review and comparison.

Summary of Analysis

SCE provided CYME models for 15 circuits that traverse high fire risk areas. A total of 39 protection relays provide protection on these circuits. The protective device coverage of each fast curve setting was evaluated with the coverage evaluation being based on a percentage of the circuit the fast curve setting would detect and clear faults. The study revealed 11 of the 15 circuits do not provide 100% circuit coverage, with 6 circuits having less than 50% circuit coverage. In general, the line relay settings at the substation will cover their zone of protection for ground faults, but the phase fault coverage is not desirable. The Remote Automatic Recloser (RAR) fast curve settings are not providing adequate coverage for phase or ground faults. Many of the RARs have ground fault tripping times comparable to the fast curve setting (less than 2.0 cycles) while others are clearing slower than half a second for end-of-line (EOL) faults.

Reducing the fast curve pickup of line relays and reclosers would be a means of increasing circuit coverage. However, there will be a limit on how low these settings can go before they cause other abnormal conditions to result in a trip when they should have typically remained closed. This upper limit is estimated by modeling a fault induced delayed voltage recovery (FIDVR) event caused by the stalling of single-phase compressor motors associated with air conditioners due to abnormally low momentary voltages. During this time, these loads can draw upwards of 6 pu (per unit) current. This study models three-phase and single-phase FIDVR events on each of the 15 circuits to determine the peak current through each line relay and recloser for a set of load compositions. For the analyzed circuits, it would be appropriate to reduce the phase fast curve setting to 2.3 times the minimum trip while not tripping on a motor stall FIDVR event assuming no more than 30% compressor load on the circuit.

Modifications to the philosophy were investigated to increase circuit coverage of fast curve settings. Reducing the existing phase and ground fast curve settings of 4.0-5.0 times minimum trip to 1.0-2.0 will increase sensitivity of the settings and provide greater circuit coverage. The present methodology has the fast curve setting being disabled when the breaker/recloser is closed in to reenergize the circuit. This process can occur multiple times while patrolling the circuit to find the cause of an outage. Nuisance tripping on cold load pickup is not a concern for the setting. While it may be possible to determine a phase minimum trip setting capable of riding through cold load pickup, it is beyond the scope of this study. Tripping on the ground instantaneous during cold load pickup can be reduced if the circuit is well balanced. Reducing the phase minimum trip to 1.0-2.0 times should not have negative operational effects under normal operating conditions. It was determined a phase minimum trip of 2.3 times is recommended.

At present, the ground fast curve settings are not implemented in the RAR settings methodology. As a result, the RAR settings provide minimal protective coverage for phase to ground faults. A ground instantaneous element set at 5.0 times the minimum trips will achieve 100% coverage for phase-to-ground faults in the protective zone. This setting will provide 100% coverage for RAR and settings. For the analyzed circuits, setting a ground fast curve relay setting to 5.0 times the ground minimum trip on both line relays and reclosers appears to be an appropriate means of increasing system sensitivity without resulting in false tripping for 38 of the 39 lines/reclosers studied assuming a 30% compressor load.. It was determined a ground minimum trip of 5.0 times is recommended.

Another option investigated was the inclusion a negative sequence element in the philosophy. The addition of a negative sequence element allows for more circuit coverage for unbalanced phase to phase and phase to ground faults allowing less sensitive phase settings. Using the negative sequence element 100% circuit coverage for line-line and single-line to ground faults would be possible with a setting of 2.3 times the minimum trip.

SCE does not have a high-speed communications network in place for the majority of these high fire risk circuits. The lack of communications network will limit the potential vendor solutions available to increase protective reach and tripping speeds. Schweitzer Engineering Laboratories (SEL) manufactures a fault detector and transmitter combination that can be leveraged to extend protective reach. SEL indicates the fault could be detected and transmitted to the relay in 6 ms. The implementation would be limited to SEL relays as the mirror bit communication protocol is used. The recloser controls in the high fire risk areas are SEL-351R’s. The fault detection units could be incorporated with the RARs to increase the protective reach of the fast curve setting.

The present fire mitigation methodology for 2 utilities are discussed. Both entities utilize a fast curve to implement a fuse saving scheme in their everyday protection philosophy. During high fire days reclosing is disabled and the protection will only trip via the fast curve setting, significantly reducing tripping times. These settings are not as fast as an instantaneous element as used by SCE, but they do not require a multiple of the time over-current setting. These settings generally have greater circuit coverage.

SCE FAST CURVE PROTECTION REVIEW

SCE’s fast curve protection philosophy consists of a sensitive instantaneous element, referred to as a fast curve setting, that can be enabled or disabled within the relay control. The fast curve setting is implemented in all electronic line relays and automatic reclosers on distribution lines that traverse high fire risk areas. These protection elements can be controlled locally at the relay controller or remotely using SCADA (if available). The fast curve protection settings are enabled per System Operating Bulletin 322.

Line relays and reclosers within the affected areas will have the fast curve settings enabled and all automatic reclosing will be disabled. Following a fast curve trip event, the line or line section will be patrolled. Once the patrol is complete, the fast curve settings are disabled before testing the line or line section. If the line or line section tests good, the fast curve settings are restored while any remaining line sections are patrolled. The fast curve settings are disabled again before testing any other line sections. Once power is successfully restored the fast curve settings will be enabled. This process negates the concerns of the fast curve settings being too sensitive to allow for cold load pickup currents.

Line Relay Philosophy

Line relay fast curve protection philosophy follows the SCE provided flow chart listed in Appendix A. The fast curve settings include phase and ground overcurrent protection. Per the flow chart, the line relay instantaneous (IT) element will never be set more sensitive than 4.0 times the phase/ground time overcurrent minimum trip settings. The setting will have a maximum of a 2.0 cycle delay.

If the calculated close-in fault duty on a line out of the substation is below 11 kA, and there are fast curve enabled reclosers on the line, the line relay setting will be increased to limit overreaching the downstream reclosers. The line relay fast curve setting will be set to overreach the furthest downstream recloser by 20%. The furthest downstream recloser is defined as the recloser with the lowest calculated fault duty in the zone of protection of the line relay. By developing the setting based on the furthest recloser downline it confirms the setting will cover all downstream reclosers.

The consequence of raising the fast curve setting is that it could be increased to a point where all the circuit branches in the zone of protection are not fully covered, especially where there are long branches of circuit not protected by recloser(s). These scenarios should need to be assessed on a circuit by circuit basis.

The line relay ground fast curve setting is not implemented in circuits utilizing a low-ground or sensitive-ground scheme. The maximum ground fault magnitudes for these circuits are less than 300 A and may be as low as 50 A. In many cases the ground protection for these schemes is handled by a non-directional overcurrent relay sourced by a single CT connected in the secondary of a grounding PT, or by a voltage relay measuring broken delta connected voltage. In these cases, the current fast curve strategy is not compatible with this type of grounding and relaying scheme.

Remote Automatic Recloser Philosophy

SCE's RAR fast curve settings utilize phase instantaneous overcurrent settings. The IT setting is 5.0 times the phase time overcurrent minimum trip. There is no intentional delay for the phase overcurrent setting. The setting will pick up ground faults but will have limited sensitivity since the phase time overcurrent is not set to be sensitive to ground faults in its zone of protection. The assumption for only utilizing the phase overcurrent element is the ground relays will be sensitive and fast enough to meet SCE fire mitigation goals.

SCE Protection Settings Guidelines

The fast curve setting sensitivity is directly tied to the time overcurrent setting sensitivity. This relationship greatly affects the circuit coverage of the fast curve settings. SCE has the following setting guidelines for its time overcurrent elements protecting distribution circuits:

- Phase Sensitivity:
  - Phase minimum trip ≥ 1.5 times peak 10-year loading (most cases)
  - Phase minimum trip ≥ 1.3 times peak loading (for 12 kV and 16 kV circuits designed for a maximum of 550 A loading)
  - Phase minimum trip < $EOL_{LL}/2$
- Ground Sensitivity:
  - Ground minimum trip = ~25-30% of Phase minimum trip
  - Ground minimum trip < $EOL_{SLG}/5$
- Where EOL values are the minimum fault values in the relay's zone of protection. The setting is not required to be sensitive enough to see beyond fused sections of the circuit.

If the existing ground overcurrent sensitivity guidelines are followed, a setting 4.0 times the ground minimum trip should cover 100% of the ground faults in the relay's zone of protection. Circuits with EOL multiples near the phase guidelines may have limited circuit coverage. A setting of 4.0 times the phase minimum trip could be 2.0 times greater than the EOL phase time overcurrent setting. In these cases, the fast curve setting would only cover 50% of the phase faults in its zone of protection.

SCE also has an EOL clearing time guideline for distribution protection relays. The clearing time guideline is to trip in less than 2.0 seconds for EOL faults on a typical urban circuit; however, long circuits in the rural areas may have EOL clearing times longer than 2.0 seconds. If the fast curve setting does not cover 100% of a device's zone of protection, the time overcurrent element will operate based on its Time Current Curve (TCC) to clear the fault.

Fuse Changes

SCE is installing current limiting fuses in their high fire risk circuits. These fuse types release less hot/burning material when clearing a fault when compared to the expulsion type fuses typically used by SCE. Also, if the fault current is greater than the current limiting rating the fuse design will actively limit the current and the fuse will clear the fault in half of a cycle. These fuses limit the overall energy of a fault and provide very fast clearing. The fast clearing times and current limiting capabilities will limit the required reach for the fast curve settings, effectively increasing the circuit coverage of the fast curve settings.

CIRCUIT ANALYSIS

To evaluate the effectiveness of the fast curve protection philosophy a sample of 15 circuits consisting of 39 protection relays were studied. All 15 circuits were analyzed using the available CYME models and SCE Redbook source impedances. The fast curve settings for each of the 15 circuits (settings are shown in Appendix D) were evaluated for the overall coverage in their zone of protection. The zone of protection was defined to be all areas downline from fuses but would not look past breakers and reclosers. The setting protective zone was evaluated past fuses because the desired result is to trip near instantaneously for faults. The fast curve setting is not intended to coordinate with fuses therefore the fast curve setting protective zone was analyzed past fuses. The settings were only evaluated for overhead sections of line in the device's zone of protection. Underground construction is not a major concern for wildfires and was omitted from the analysis.

The existing Line and RAR fast curve settings provide 100% phase and ground coverage for only 3 of the 15 circuits studied. Of the 39 devices, 13 provide 100% phase coverage of their protection zone while 15 provide 100% ground coverage. Figure 1 below shows the total circuit coverage provided by the Line and RAR phase and ground fast curve settings. Refer to Table B-1 in Appendix B for the fast curve settings evaluation.

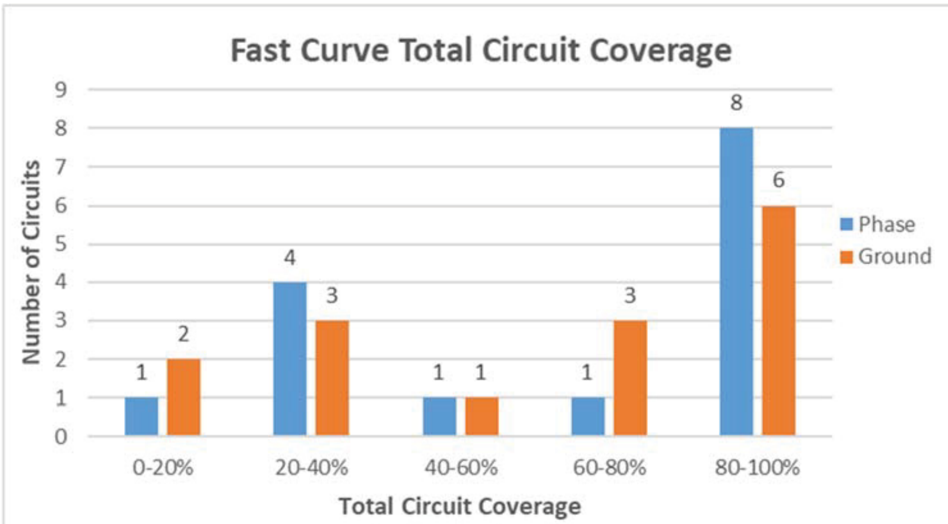


Figure 1 – Existing Fast Curve Settings Coverage

The RAR fast curve settings did not include the ground element in the philosophy with the assumption the existing ground element settings would clear in a comparable time. The following table shows the EOL clearing times for the 25 RARs studied in the 15 circuits.

Table 1 – RAR EOL Clearing Times

Substation	Circuit	RAR ID	Phase EOL (A)	Phase EOL Clearing Time (s)	Ground EOL (A)	Ground EOL Clearing Time (s)
[redacted]						

Table 1 – RAR EOL Clearing Times						
Substation	Circuit	RAR ID	Phase EOL (A)	Phase EOL Clearing Time (s)	Ground EOL (A)	Ground EOL Clearing Time (s)
[redacted]						

From the results in Table 1, there are 7 RAR phase settings with EOL clearing times less than 0.5 seconds with 10 greater than 1.0 second. The maximum clearing time for the phase elements is 6.4 seconds. There are 16 RAR ground settings with EOL clearing times less than 0.5 seconds and 6 greater than 1.0 second. The maximum clearing time for the ground elements is 1.3 seconds. While these meet the typical clearing times for regular time overcurrent settings, 0.4-2.0 seconds is a long time to clear a fault during high fire risk events.

It should be noted that some of the RAR settings had ground EOL clearing times of less than 5.0 cycles. These RAR settings had ground minimum trips of 20 A or less. These low minimum trip values are typical of three-wire distribution design implemented by SCE. All loads are connected using line voltage resulting in low amounts of load current imbalance. The low current imbalance allows for the RAR settings on the circuit to be set more sensitive and resulting in faster clearing times. This is not always the case as there are RAR settings with low minimum trip settings (50A or less) that have almost 1.0 second clearing times. All the settings would have 100% ground coverage, and trip instantaneously, if they were to follow the 5.0 times minimum trip philosophy. SCE also implements a four-wire distribution circuit design where many loads are connected using phase-to-ground voltage and have a larger imbalance current when compared to the three-wire design. These circuits would see the same benefits if the ground fast curve settings were to be implemented.

A/C Stalling Studies

Reducing the fast curve minimum trip settings may be a means of increasing the system sensitivity. However, the maximum load current for a given system must be known such that a new lower setting does not trip the system unnecessarily. The approach taken here is to model FIDVR events to find the maximum load current that a given circuit may draw without triggering a relay operation. Single-phase compressor motors associated with air conditioner units can enter a stall or locked-rotor condition which can result in a large current demand until the motors either recover from the transient or disconnect. During a stall, a single-phase compressor motor can draw up to 4.5 pu real power and 4.0 pu reactive power [1] resulting in approximate current draws of 6 pu depending on voltage levels. This type of event was modeled on the 15 circuits with the objective of determining an upper limit on load current through the line breakers and reclosers which should not result in a trip.

The 15 circuits were built in MATLAB/Simulink (R2019b) using impedance and loading data from provided CYME files. Each circuit was aggregated to include the feeder source with line relay, RARs, capacitors, and other significant locations as needed to provide a good representation of the feeder. The loading of the circuit was modeled as a ZIP+IM type load. This consists of a portion of the load represented by single-phase induction machines (IM, A/C compressor load) with the remaining portion split into thirds between constant impedance (Z), constant current (I), and constant power (P) loading. The loading on each circuit was set to be 80% of the phase minimum trip for each feeder breaker for consistency between circuits. The load power factor was set to 0.95. In many cases, this level of loading is well above the maximum loading of a circuit and should provide a conservative approach regarding upper current limits. All capacitor banks for each circuit were in service and no distributed generation was modeled.

For each circuit, 6 cases were simulated. Either a three-phase or single-phase disturbance was modeled by a drop in voltage seen at the head of each circuit from 1 pu down to 0.25 pu for 0.1 s before recovering. This drop in voltage is what triggers all compressor motors on the affected phase(s) to enter a stall mode. The percentage of the load comprised of compressor motors was either 20%, 40%, or 60%. The tables in Appendix G contain the peak RMS currents, negative sequence currents, and zero sequence currents seen by each relay in the 15 circuits for both a three-phase and single-phase event. Those tables also compare the peak current to the phase minimum trip for the RMS and negative sequence peak values as well as compare the peak to minimum ground / neutral minimum trip for the zero sequence peak values.

Figure 2 below shows the peak RMS values during a three-phase event as a multiple of the phase minimum trip from Appendix G shown compared to the percentage of the load consisting of compressor loading. The peak RMS currents were all ≤ 1.99, ≤ 2.57, and ≤ 2.96 multiples of the phase minimum trip current for 20%, 40%, and 60% compressor loading respectively. These results for the three-phase event are like those of the single-phase event which is shown in Figure 3. In general, the peak RMS values for the single-phase event are slightly lower than those of the three-phase event.

A value of 60% of the load consisting of compressor loads is likely an extreme case even for a hot environment such as the American southwest. Values of 20% are more realistic as an upper value with 40% being a more plausible peak composition. Obtaining detailed information about the amount of any given load consisting of single-phase compressors is difficult so a reasonable assumption is made in this study. Reducing the phase fast curve relay settings to 2.3 times the phase minimum trip appears to be an appropriate means of increasing system sensitivity without resulting in false tripping for those circuits studied assuming a 30% compressor load.

Setting a ground fast curve relay setting to 5.0 times the ground minimum trip on both line relays and reclosers appears to be an appropriate means of increasing system sensitivity without resulting in false tripping for 38 of the 39 lines/reclosers studied assuming a 30% compressor load.

This minimum trip recommendations are based on the results of this study and conferring with SCE.

Another observation is that the line breakers are much more closely grouped when compared to the RAR curves. This is likely because the load measured through each line breaker was tuned to draw 80% of the phase minimum trip at that line breaker. Having that consistency from model to model is what likely causes the curves to be similar.

The data shown in Figure 4-Figure 7 represent the negative and zero sequence peak magnitude current for three-phase and single phase events based on the data in Appendix G. This data is most relevant to the setting of the ground fast curve settings on four wire residual ground overcurrent protected circuits. The ground minimum trip values were used to scale the zero sequence currents. The negative sequence curves appear to have somewhat similar curves to that of the RMS current values albeit at lower values. Zero sequence curves are much less consistent in their groupings which suggests difficulty in determining a general protection setting based on zero sequence current. For 4 of the circuits [redacted], large zero sequence impedances required transformers on the aggregate loads to have a delta in the primary winding. This configuration was necessary given the high zero sequence impedance of the system and the high loading which could be unbalanced. The result of this delta winding is the elimination of most of the zero sequence current through the line relays and reclosers. Factors such as this make relays based on zero sequence current difficulty to implement in a broad, universal scheme. It should also be noted that for [redacted] the ground / neutral minimum trip value is not current but rather voltage.

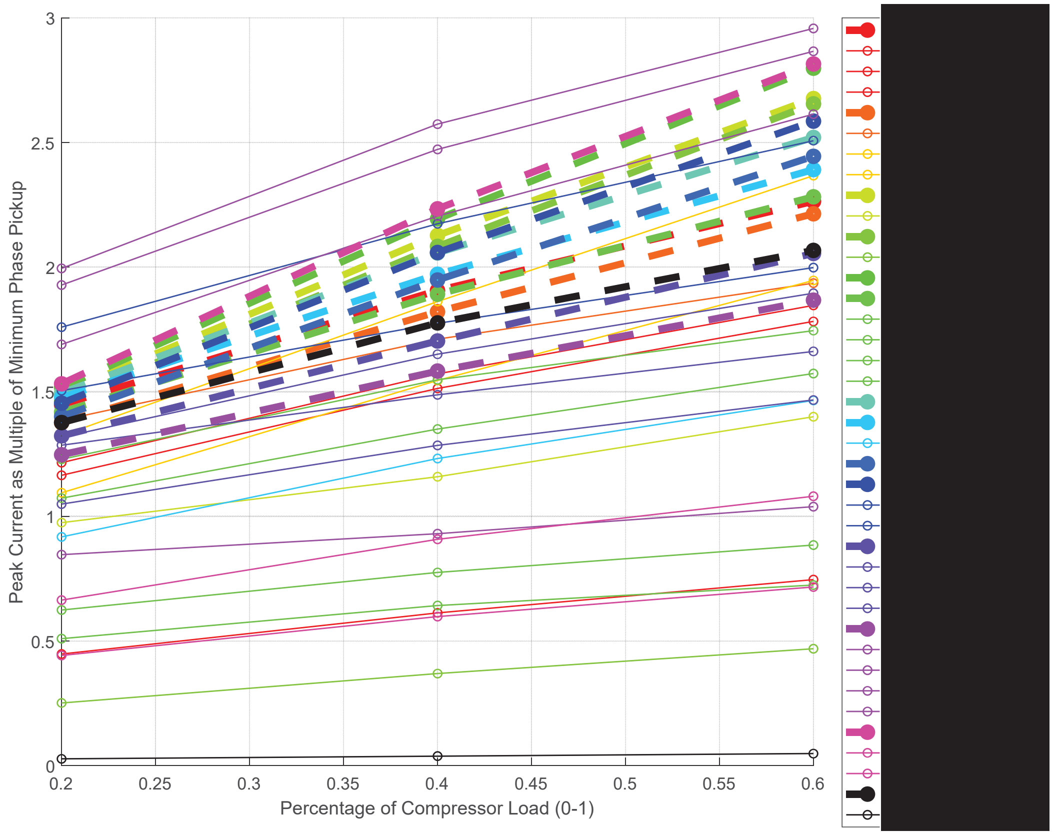


Figure 2 – Peak Relay RMS Current for Three-Phase FIDVR Event

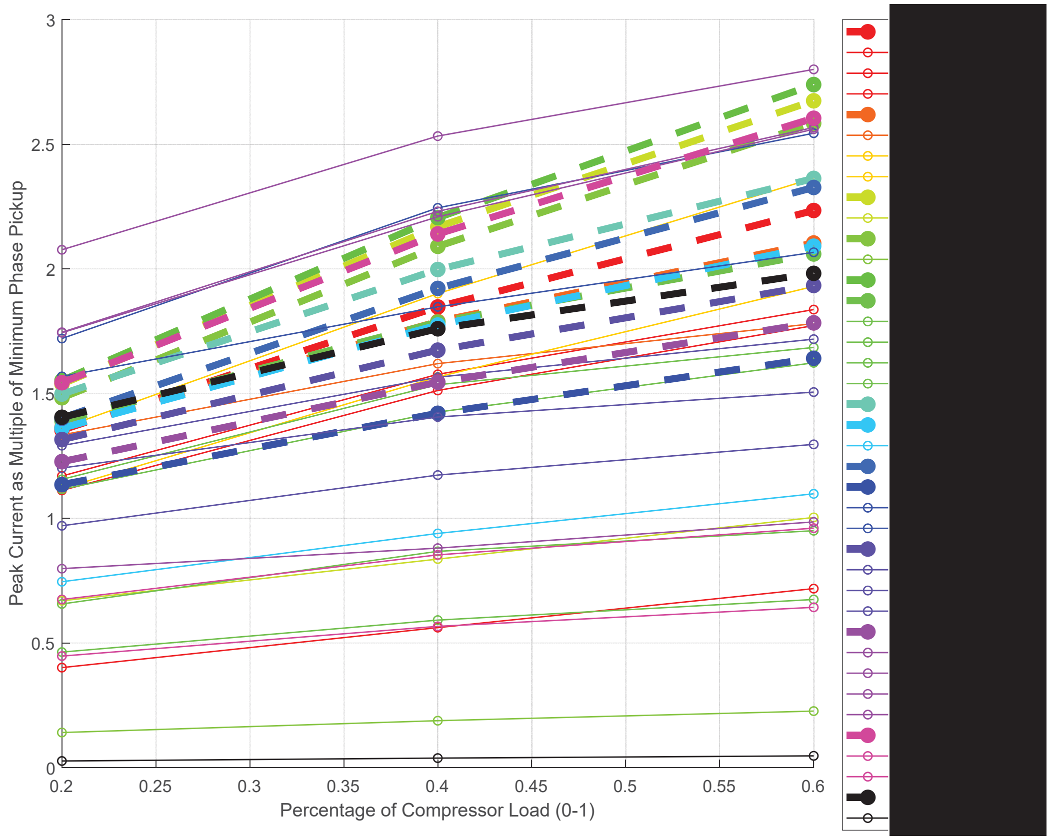


Figure 3 – Peak Relay RMS Current for Single-Phase FIDVR Event

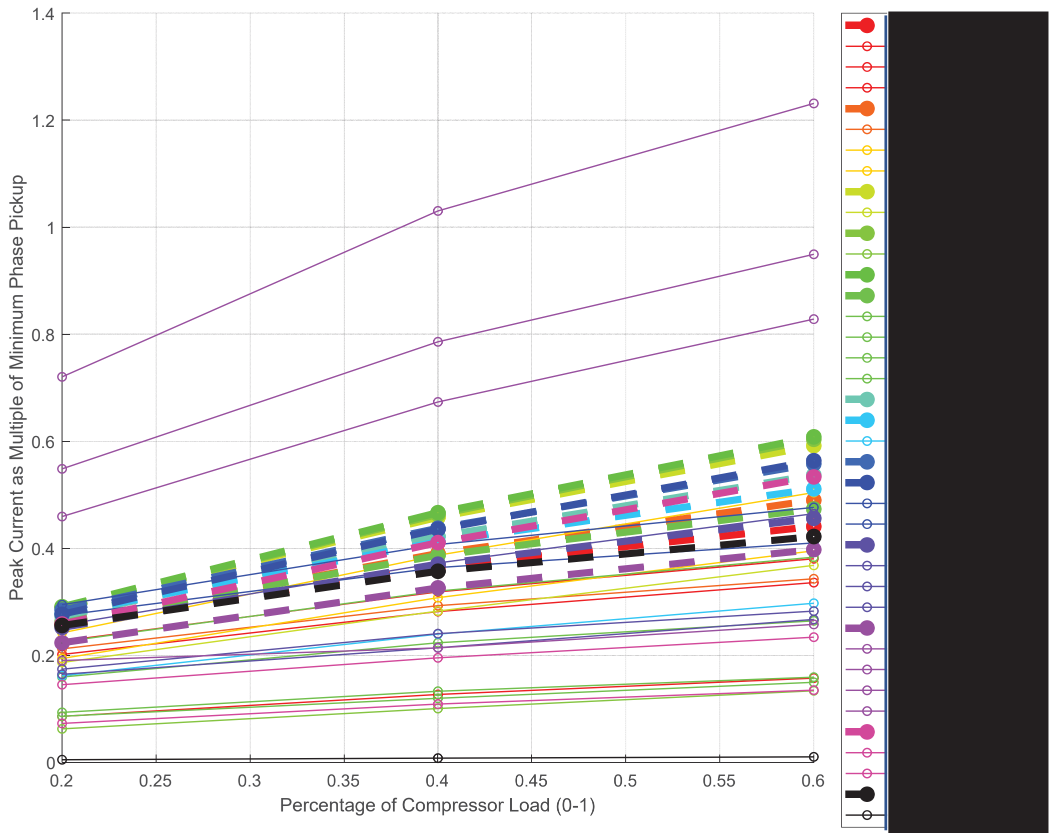


Figure 4 – Peak Relay Negative Sequence Current for Three-Phase FIDVR Event

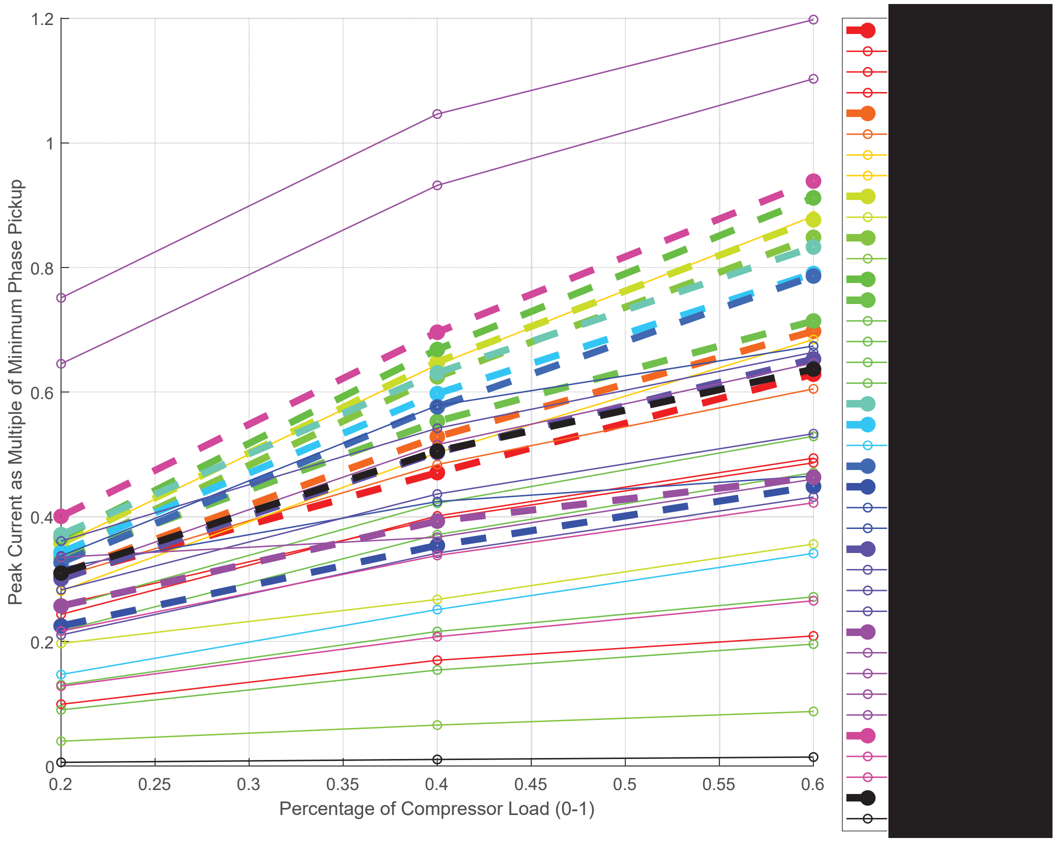


Figure 5 – Peak Relay Negative Sequence Current for Single-Phase FIDVR Event

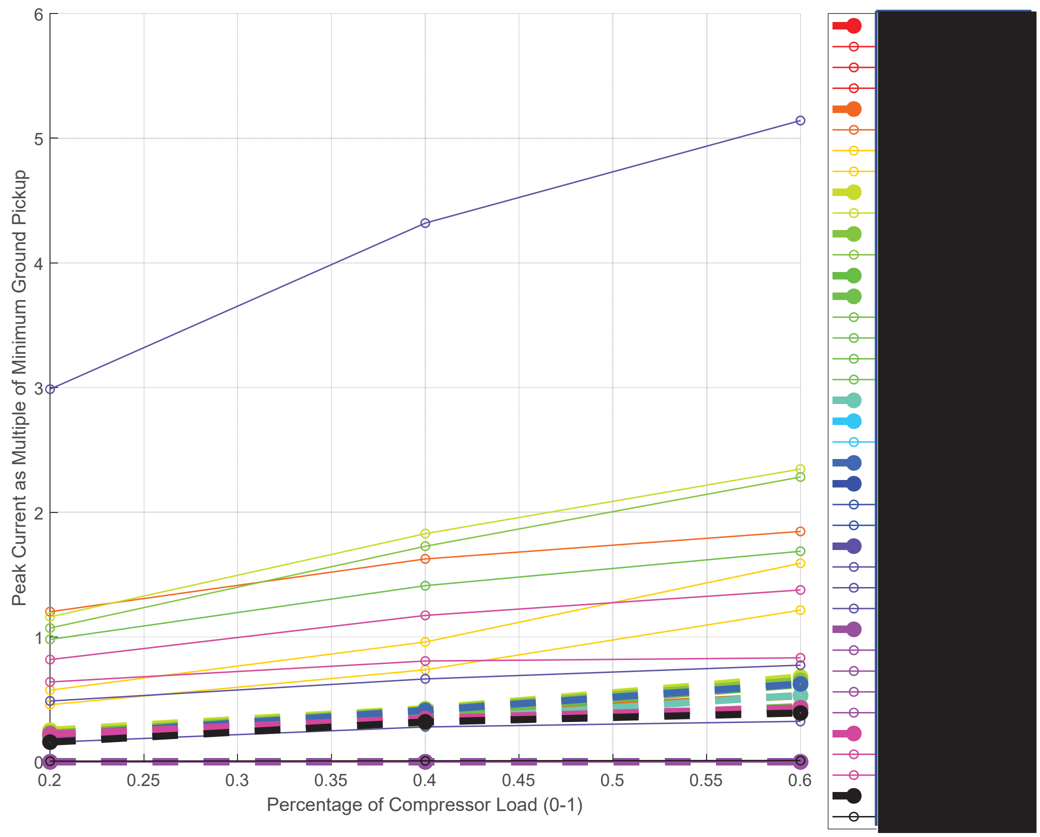


Figure 6 – Peak Relay Zero Sequence Current for Three-Phase FIDVR Event

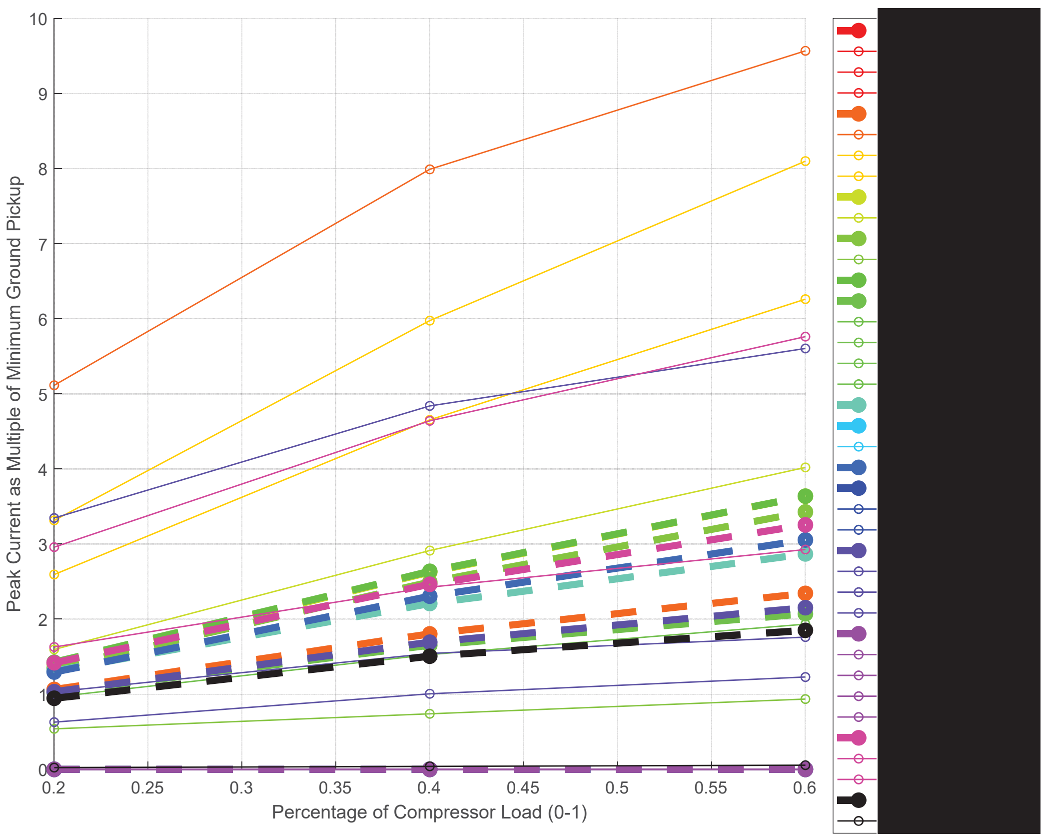


Figure 7 – Peak Relay Zero Sequence Current for Single-Phase FIDVR Event

[redacted] *FIDVR Event Analysis*

The purpose of this section is to provide an overview of the response of several distribution relays to a 115kV event in the [redacted] System, and address whether the data captured during this event can be used to improve the proposed Fast Curve setting philosophy.

Following a fault on a 115kV capacitor bank, a dip in system voltage caused several distribution relays to trip on Ground Time Overcurrent elements. The following is a summary of the event data extracted from the relays.

Event:

Flashover of the [redacted] capacitor bank at [redacted] Substation due to a weed contacting phase B of the capacitor rack. A review of the capacitor bank relay event file showed a B phase fault current magnitude of approximately 9,840 A. The instantaneous overcurrent element asserted within the first half cycle of the fault, and the fault was cleared approximately 43.7 ms following fault inception. Once the fault cleared the B phase showed a continued undervoltage condition of approximately 53kV (0.78 per unit of pre-fault). This condition persisted for 1.2 seconds prior the end of the event record. The following table details the distribution relays response to the event.

Table 2 – Distribution Relay Response 07/11/2020 Event

Relay	Line	Event Trigger time	Time to trip (sec)	Low Phase Voltage	Phase Current (Note 1)	Ground Current (Note 1)
[redacted]		16.39.18.991	51G @ 4.695	VC 0.8 pu	IA = 223A IB = 316A IC = 483A Pickup Mult = 0.67	IG = 333A Pickup Mult = 1.8
		16.39.18.967	51G @ 2.273	VC 0.78 pu	IA = 387A IB = 307A IC = 722A Pickup Mult = 1.0	IG = 448A Pickup Mult = 2.5
		16.39.18.960	51G @ 7.4	VC 0.78 pu	IA = 469A IB = 347A IC = 581A Pickup Mult = 0.81	IG = 255 A Pickup Mult = 1.4
		16:35:53.42	51G @ 2.841	VBn 0.83 pu VCn 0.87 pu (Note 2)	IA = 319A IB = 320A IC = 706A Pickup Mult = 0.98	IG = 472 A Pickup Mult = 2.6

[redacted]	15:10:07.51	51G @ 4.308	VBn 0.85 pu VCn 0.88 pu (Note 2)	IA = 183A IB = 357A IC = 581A Pickup Mult = 0.81	IG=425A Pickup Mult = 2.4
	15:10:05.55	51G @ 4.091	VBn 0.84 pu VCn 0.86 pu (Note 2)	IA = 343A IB = 291A IC = 615A Pickup Mult = 0.85	IG=378A Pickup Mult = 2.1
Note 1: Currents shown are approximate median amps, measured current varied over the course of the event. Note 2: [redacted] fault records show L-L voltages labeled kVan, kVbn, kVcn. Values are in per unit of 12.47kV L-L.					

Implications for Fast Curve setting Philosophy

The stalling event produced currents that gave maximum multiples of pickup current of 1.0 for phase and 2.62 for ground. The revised fast curve methodology with a phase setting of 2.3 x minimum trip and a ground setting of 5.0 x minimum trip would not have operated for this event.

The relays all tripped on ground time overcurrent. While the event resulted in low multiples of the pickup setting, the event was sustained long enough for the protection to timeout. The longest captured event was 7.4 seconds. Supporting figures are found in Appendix H.

OTHER JURISDICTIONS FIRE MITIGATION PHILOSOPHY

Many utilities are implementing fire mitigation strategies in California and across the United States. The philosophies range from more stringent tree trimming policies, installing current limiting fuses, converting to covered overhead conductor, converting to underground construction, or switching to a more sensitive/faster protection scheme as SCE has done. The following are protection schemes implemented by 2 utilities aimed at preventing wildfires.

Utility A

This utility's service territory includes southwest United States. Their fire season tends to run 8-10 months of the year.

- Normal Operation Philosophy and Criteria:
  - Phase Time Overcurrent:
    - Pickup set at 1.5-2.0 times load at device
    - Set less than 1/3 of lowest available phase fault current at end of protective zone
    - Set less than 85% of upstream device phase setting
    - Fuse saving on phase and ground elements
  - Ground Time Overcurrent:
    - Pickup set less than 1/3 of lowest available maximum ground fault current at end of protective zone
    - Set less than 85% of upstream device ground setting
  - Phase/Ground IT:
    - Set greater than 1000 A
    - Set less than 90% of upstream IT element
    - Set less than 90% of available phase/ground fault current at device
    - Set greater than 110% of phase/ground fault current at nearest largest downline device
    - Set with 3.0 cycle delay
- Fire Season (Fast/Sensitized) Operation Philosophy and Criteria:
  - Phase/Ground Time Overcurrent:
    - Pickups set approximately 75% of normal pickup
    - Reclosing is disabled
    - Downstream fuse coordination is sacrificed when this setting in active.
    - Same protection curves are utilized between fire season and normal operation.
  - Phase/Ground IT:
    - Pickup set same as Normal Operations
    - Lockout enabled
  - High impedance fault detection always on. Utility has custom SEL logic for tripping using the Hi-Z tripping quantities.

When the fire mitigation settings group is active the time overcurrent sensitivity is increased by 25%. The reclosing is disabled, and the relay will trip and lockout on one fast curve shot. The fast curve is not standardized across all relays. The curve settings typically used are U4 (extremely inverse) or a 163 recloser curve. The curve type may vary from setting to setting depending on what will work best for coordination on the feeder.

The use of the IT setting can give very fast clearing for portions of the protective zone but is unlikely to give 100% coverage. Fire mitigation was not the goal of implementing the IT setting. Increasing the sensitivity of the time overcurrent elements will increase the protective reach of the setting and will consequently decrease relay operating times. How much affect increasing sensitivity has on relay operating times greatly depends on the curve type and available fault current. The increased sensitivity will always have a positive effect on reducing relay operating times.

Utility B

This utility's service territory includes parts of the mountain west

- Normal Operation Philosophy and Criteria:
  - Phase Time Overcurrent:
    - Pickup set at one-half lowest phase-to-phase end-of-line fault
    - Set at 100-140% of line conductor rating
    - Set at 100% of connected kVA
    - Fuse saving scheme is implemented with one fast shot on phase and ground elements.
  - Ground Time Overcurrent:
    - Pickup set less than 1/3 of lowest available maximum ground fault current at end-of-line fault
    - Set at 100% highest single-phase connected kVA
    - Set at 33% of phase pickup
- Patrol Philosophy and Criteria:
  - Slow setting only with 1 shot to lockout. Enabled if a patrol has been conducted and nothing has been found
- Red Flag (Fire Mitigation):
  - Reclosing disabled
  - Slow curves disabled
  - 6.0 cycle time adder incorporated to coordinate with downstream reclosers.
  - Downstream fuse coordination is sacrificed when this setting in active.
  - Desired future implementation to include the high impedance detection logic
  - Replacing all expulsion type fuses with current limiting type fuses

When the fire mitigation setting is active the relay will trip and lockout on the fast curve setting. All relays have a fast curve utilizing the 101 recloser curve on phase and ground overcurrent elements. The 101 recloser curve will trip in approximately 1.0 cycle at 5.0 times the pickup value. The slowest the curve will detect a fault and trip is around 6.0 cycles. Included with the 6.0 cycle time adder the recloser will trip for phase and ground faults in approximately 10.0 cycles accounting for the recloser clearing time.

The protection sensitivity requirements dictate that the relays zone of protection must extend past downstream fuses. This methodology leads to the fast curve being set sensitive enough to detect and clear faults on all sections of line downstream. When the fire mitigation setting is active all phase and ground faults should be detected and cleared in 10.0 cycles or less.

This settings methodology is currently being implemented and has not been active for a fire season at the time of this report. More time will indicate is this is an effective protective settings solution for fire mitigation.

RECOMMENDATIONS

Reducing the Minimum Trip Multiple

To gain better circuit coverage the protection elements will need to be set more sensitively. Lowering the minimum trip on the fast curve setting will increase sensitivity and circuit coverage. Figure 8 and Figure 9 show the required time overcurrent multiples to provide 100% coverage for the zones of protection for the 15 sample circuits.

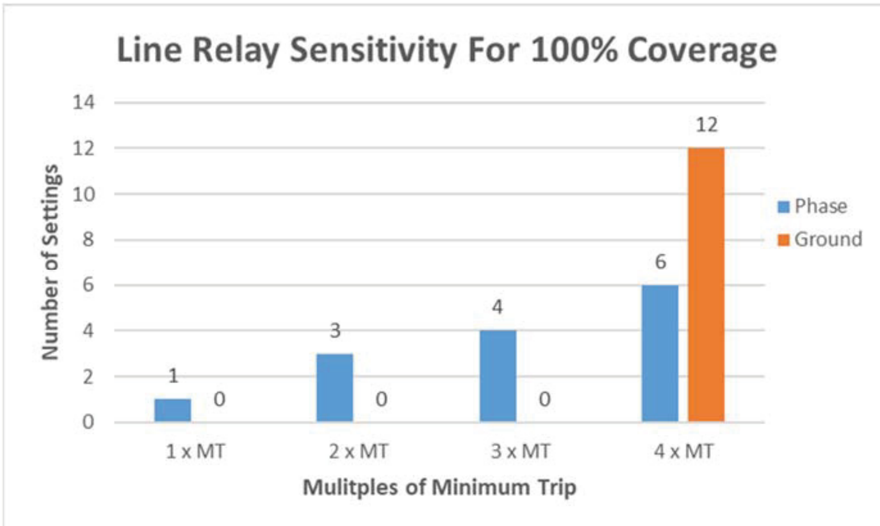


Figure 8 – Line Relay Required Sensitivity to Achieve 100% Coverage

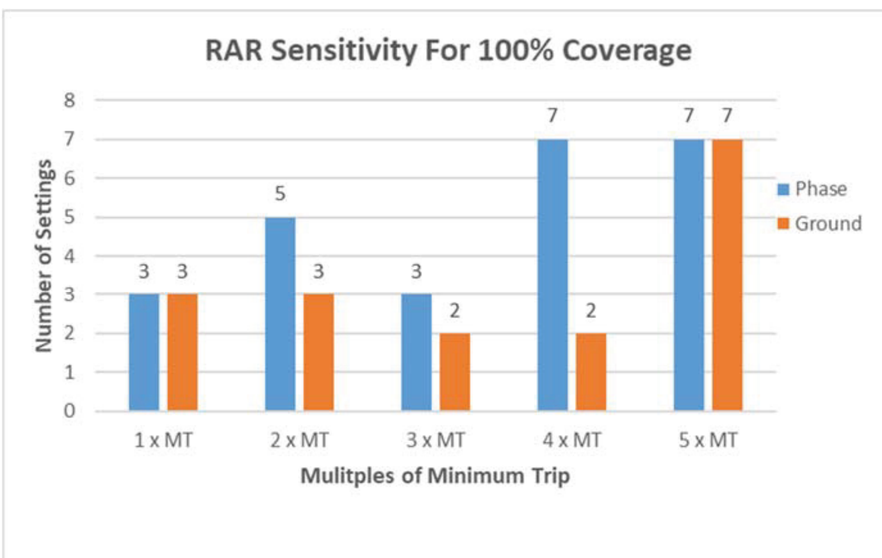


Figure 9 – RAR Required Sensitivity to Achieve 100% Coverage

These figures show, in most cases, a fast curve setting of 2.3 times the phase minimum trip will yield adequate sensitivity to cover the zones of protection for phase faults. This is the expected result given the required EOL fault vs multiple of minimum trip guidelines for distribution circuits discussed in SCE setting guidelines. Figures detailing the existing minimum trip range for each of the 15 circuits can be found in Appendix E.

Incorporating the Ground Element

The existing RAR fast curve settings do not utilize the ground protection element. Not including the ground element causes the phase element to be relied upon for quickly clearing phase-to-ground faults. From the analysis on the existing settings this leads to minimal ground fault coverage. A fast curve ground setting of 4.0 times the minimum trip would give 100% coverage for ground faults within the protective zone. This setting will give 100% coverage for all RARs and line relays studied in this report.

Negative Sequence Protection Elements

The data from the 15 circuits showed that the fast curve phase elements were an issue for all relays and ground sensitivity was an issue for the RARs. The negative sequence element provides added sensitivity for line-to-line faults and will also be able to detect ground faults. The phase domain to sequence domain relationship for line-to-line faults is:

$$I_{\emptyset} = \sqrt{3} * I_2$$

Where,

- $I_{\emptyset}$ is the phase current measured by the relay
- I_2 is the calculated negative sequence current

The negative sequence element will be $\sqrt{3}$ more sensitive than a standard phase overcurrent relay setting. Another benefit of the negative sequence element is it is set based on circuit imbalance rather than peak loading. Load is mostly a balanced condition consisting of small magnitudes of negative sequence currents. The ground elements are already set to be above potential imbalances on the circuit so the negative sequence element can match the ground setting. The ground setting is typically set 25-30% of the phase element pickup. If the negative sequence element is set similar to the ground element minimum trip, the relay would become approximately 6.0 times more sensitive to line-to-line faults when compared to the phase element.

The negative sequence element cannot replace the phase overcurrent element but can be added to the existing philosophy to gain better line-to-line fault coverage. For three-phase faults, the negative sequence current is near zero and would not provide adequate protection for these faults.

The 15 circuits previously analyzed were reevaluated to include a negative sequence overcurrent element. The protection scheme was evaluated in the following manner:

- The phase and ground pickup values remained the same as the existing settings
    - The phase element was used for three-phase fault coverage
    - The ground relay was used for single-line-to-ground fault coverage
- A negative sequence element was set to the same minimum trip as the ground relay
    - The negative sequence was used for line-to-line fault coverage

This new philosophy was evaluated to determine the required instantaneous multiple to provide 100% coverage for three-phase, line-to-line, and single-line-to-ground faults. Figure 10 and Figure 11 show the required multiples to achieve 100% circuit coverage for line relays and RARs assuming all three elements (phase, ground and negative sequence) are set with the same methodology (1 x MT, 2 x MT, etc.).

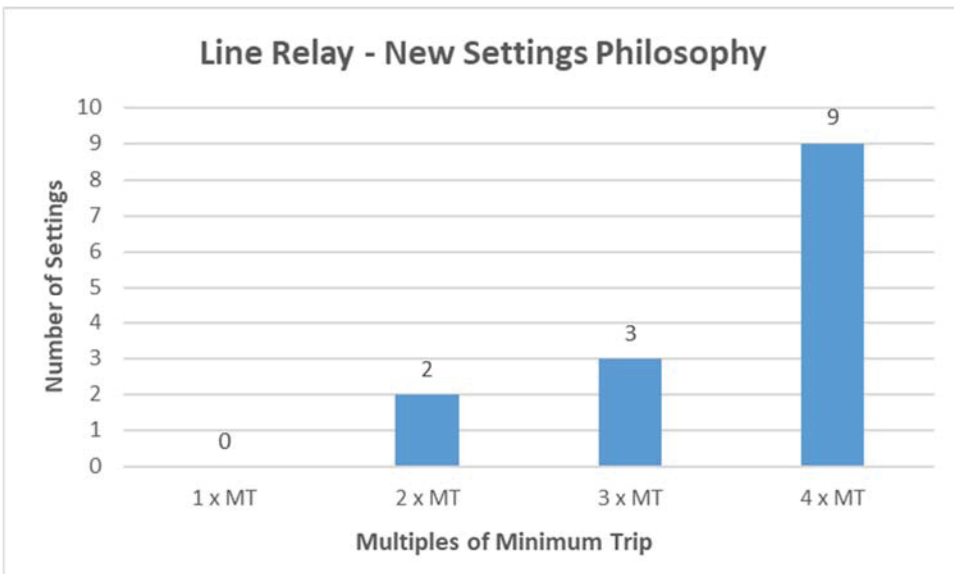


Figure 10 – Required Line Relay Minimum Trip (Phase, Ground, Negative Sequence) Sensitivity For 100% Coverage

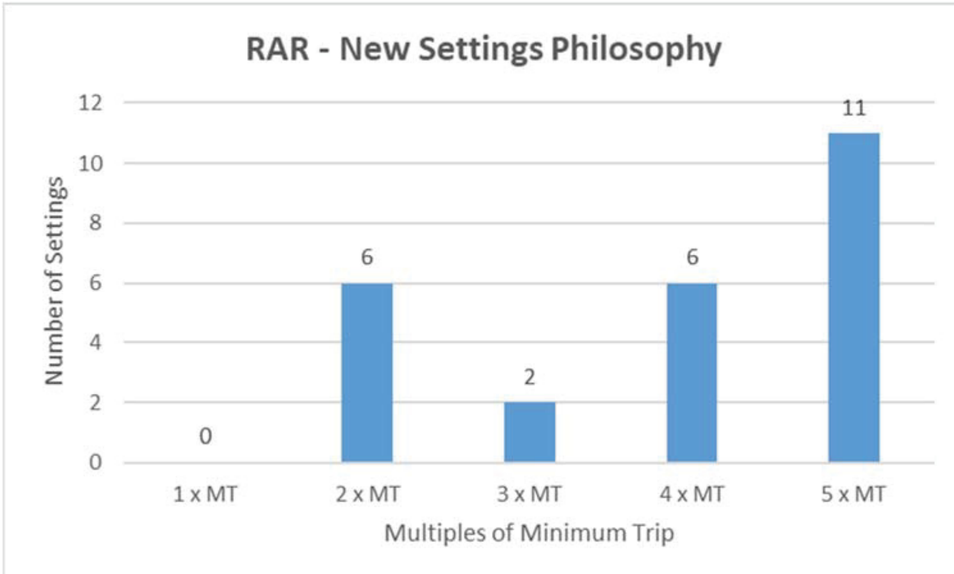


Figure 11 – Required RAR Minimum Trip (Phase, Ground, Negative Sequence) Sensitivity For 100% Coverage

Figures for each relay can be found in Appendix F. The figures in the appendix indicate the negative sequence and ground relays will provide 100% coverage at either 4.0 or 5.0 times the minimum trip. The limiting factor requiring a multiple of 2.0 or 3.0 is the phase element detecting three-phase faults. However, three-phase faults account for a small percentage of faults on a distribution system. If a consistent settings multiple across all elements and 100% coverage for all fault types is required, the setting multiple must be 2.0 or 3.0.

Incorporating Additional Technologies

SCE's high fire risk areas usually are traversed by long distribution lines located in remote areas where there are no existing communications networks to interconnect protection relays. Ideally, any additional technologies would not be reliant upon an existing communications network and would be compatible with the majority of the relays in the high fire risk areas.

SEL Fault Indicators

The analysis of the 15 sample circuits showed a majority of circuits having fast curve settings not set sensitive enough to cover 100% of the protective zones. A solution would be to add a monitoring device downline of the relays which will be able to detect faults on lines traversing the high fire risk areas. Schweitzer Engineering Laboratories manufactures a fault indicator/transmitter and receiver combination (FT50 and FR12). The FT50 is an overhead line clamp-on fault indicating device and rated for voltages up to 38 kV. It is line powered and has 8 adjustable pickup setpoints ranging from 50 to 1200 amps. The FT50 utilizes built in radio transmitters to communicate fault information to the FR12. The FR12 is the receiver unit that collects fault data from the connected FT50 units. A single FR12 may monitor up to 4 three-phase sets of FT50s (12 units).

The communications between the FR12 and FT50 utilizes a high-speed radio connection and can communicate up to 4.0 miles away (typical range). The FR12 sends the fault indicator data to the protection relay via SEL Mirror Bits. SEL has published that a fault can be detected by an FT50 and be transmitted to the protection relay in as little as 6.0 ms. The circuit analysis found some relays tripping in 500 ms or slower for end-of-line faults. Using these devices on circuits with sensitivity issues could have a real benefit to speeding up fault clearing times without reducing the minimum trip levels of the device.

Since the communication protocol is Mirror Bits between the FR12 and the protection relay, this solution is limited to SEL protection relays. The majority of substation relays in the high fire risk areas are GE or DPU relays and would not be compatible with this solution. The RARs in the system are SEL-351R relays capable of sending/receiving mirror bits. This solution could be tailored to sections of circuit downline from the RARs to increase visibility of faults in high fire risk areas.

CONCLUSION

The final results of the study found the majority of the circuits did not have fast curve settings that covered 100% of the overhead line sections of line. Many only covered 50% or less. The results of the reduced coverage is long clearing times at the end of zones of protection. SCE has over 1,000 distribution circuits that traverse high fire risk areas. If the results of this study were translated to the remaining circuits, about 40 circuits would have 100% coverage and over 500 circuits would have less than 50% coverage. To have a protection scheme that will cover 100% of the required circuit the settings will need to be set more sensitively to extend the circuit coverage.

Lowering the multiple of the minimum trip to 2.3 times minimum trip for phase elements and 5.0 times minimum trip for ground elements will yield near 100% circuit coverage. The present operations methodology has the fast curve settings disabled when closing the breaker/recloser to reenergize the circuit after a fault event, and reenabled once the line or line section has been successfully energized. This eliminates the potential for instantaneously tripping on cold load pickup. Lowering the minimum trips in this manner will make the settings more sensitive to the AC stalling events. Depending on the percent of load comprised of air conditioning, the AC stalling currents could exceed 2.0-3.0 times the phase time overcurrent minimum trip. Based on these results and conferring with SCE, it is recommended that a phase minimum trip of 2.3 be utilized to balance the increase in circuit coverage and minimize false trips during AC stalling events.

Incorporating a negative sequence element into the scheme will allow for a less sensitive setting of 4.0 times the ground minimum trip to cover 100% of the circuit for line-to-line and single line to ground faults. If the same 4.0 multiple setting were applied to the phase element, there would be marginal (~70%) coverage for three phase faults on some circuits. If a consistent settings multiple across all elements and 100% coverage for all fault types is required, the setting multiple must be 2.0 or 3.0. The 2.0/3.0 multiple may encounter issues with AC motor stalling currents and further studies may be warranted.

Many of the reclosers located on the three wire distribution circuits have ground time overcurrent settings sensitive and fast enough to give comparable protection as fast curve settings; however, there are circuits that have long clearing times. Reclosers installed on four wire distribution circuits have a larger load imbalance and typically higher ground setting than three wire circuits which may cause reduced ground fault coverage. Fault clearing times on four wire circuits are typically 0.5-2.0 seconds, with some circuits having even longer clearing times. Adding a ground fast curve setting in the reclosers on both three and four wire distribution circuits will provide rapid tripping for most ground faults in their zone of protection.

Installing communication enabled fault transmitter/receivers could be leveraged to increase the protection coverage without sacrificing sensitivity. The SEL FT50 and FR12 fault transmitter/receiver combo can push fault indications to a protective relay in 6 ms at a distance of 4.0 miles. The radio communications between the units does not require and existing communication infrastructure. This makes the unit a great fit for the high fire risk circuits without an existing communication network. However, this solution would be limited to SEL protection devices only.

Two utilities fire mitigation strategies were discussed. Each utility leverages their existing fuse saving scheme to implement their fire mitigation settings. When the setting is enabled the relay will trip once on a fast curve and lockout. Automatic reclosing is disabled when the fire mitigation settings are active. One utility implements a more sensitive time overcurrent setting to increase speed and protective reach when the setting is active. The other designed their time overcurrent protective zone to see past fuses to the end of the line. Setting the time overcurrent settings in this manner dictates that the relay fire mitigation setting will be sensitive enough to see to the end of the line.

REFERENCES

[1] Huang, Qiuhua & Huang, Renke & Palmer, Bruce & Liu, Yuan & Jin, Shuangshuang & Diao, Ruisheng & Chen, Yousu & Zhang, Yu., “A Reference Implementation of WECC Composite Load Model in Matlab and GridPACK”, 2017.

APPENDIX A – LINE RELAY FAST CURVE SETTING FLOW CHART

Fast Curve/Definite-Time Settings for Distribution Station Line Circuit Breakers

The following steps were developed as part of a methodology to address the Arcflash and Redflag mitigation settings using fast curve (definite time) settings.

1) The station short-circuit duty (SCD) must first be calculated from CAPE or Redbook to see if it is under 11kA. **If yes, proceed to step 2. If not, skip ahead to step 5.**

2) With the station SCD being under 11kA, check to see if the station is within a Bulletin 322 Area. **If yes, proceed to step 3. If not, skip ahead to step 7.**

3) Determine if the station has AR(s) immediately downstream of the station. If the station has AR(s) downstream of the line circuit breaker, then coordination with the line circuit breaker at the station is needed. **If fault duty at furthest AR is greater than 4 x Minimum Trip, then go to step 4. If not, skip ahead to step 7.**

4) Circuit breaker fast curve settings will be set at 2 cycles for 80% of max SCD of the furthest AR immediately downstream of the line circuit breaker with 4 x Minimum Trip. The objective is for the line circuit breaker to have about a 20% overreach of the furthest AR (AR with lowest short-circuit duty). This guarantees overreach of all ARs that are parallel to the furthest AR downstream, which also means AR(s) in parallel would have higher overreach the closer the parallel ARs are to the line circuit breaker relative to the furthest AR.

5) Determine if the station SCD is less than or equal to 16kA. **If yes, skip to step 7. If not, proceed to step 6.**

6) If the station SCD is over 16kA, CB interrupting time will be determined by the type and model of the circuit breaker being used. Circuit breakers will typically have 3 different interrupting times:
   A) 3 cycle CB interrupting time: Add a 2 cycle delay setting at 4 x Minimum Trip.
   B) 5 cycle CB interrupting time: Determine if short circuit duty is under or over 18kA
      i) SCD is under 18kA: Add a 2 cycle delay at 4 x Minimum Trip.
      ii) SCD is over 18kA: 0 cycle delay at 4 x Minimum Trip.
   C) 8 cycle CB interrupting time: 0 cycle delay at 4 x Minimum Trip. This will also require Arc-Flash calculations to determine PPE requirements.

7) Implement a 2 cycle delay at 4 x Minimum Trip.

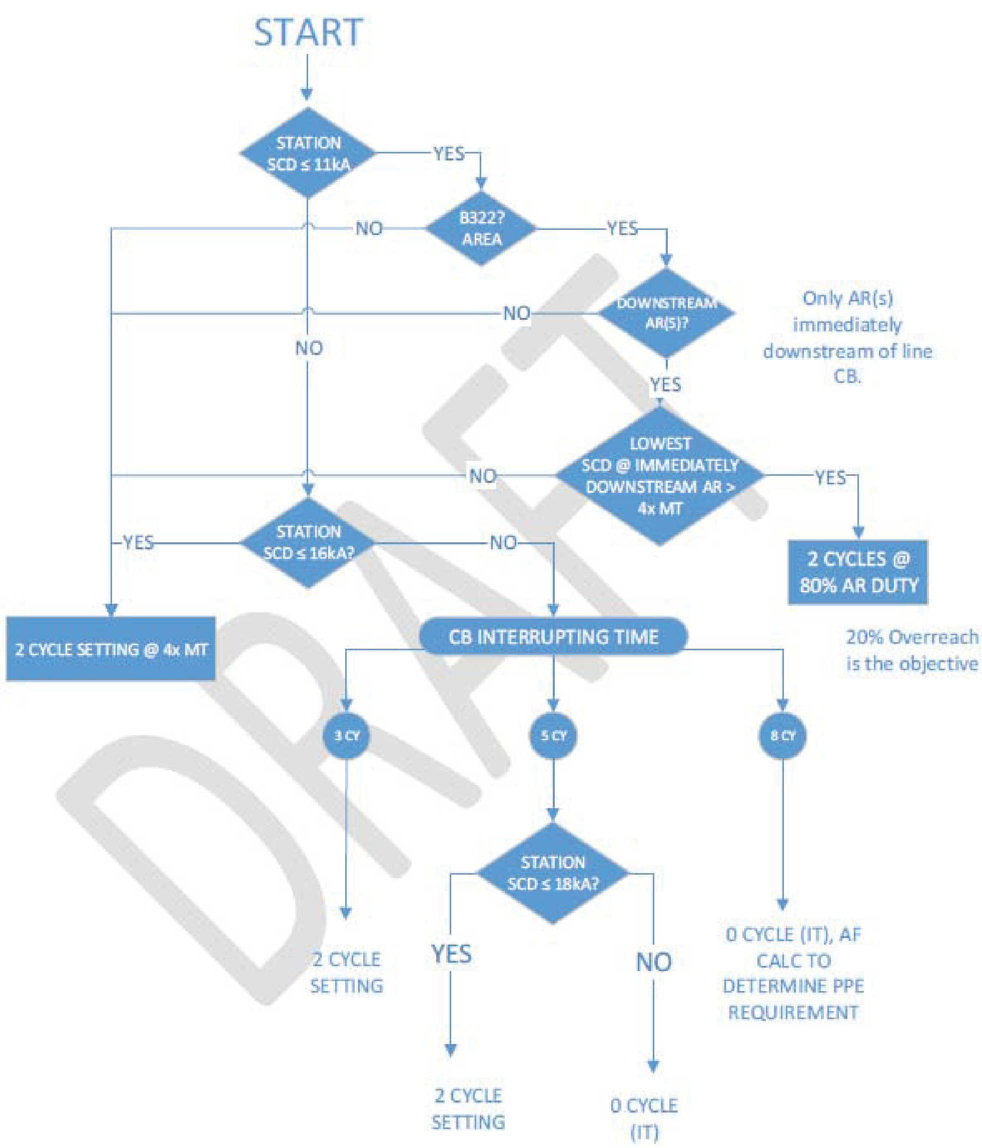
Tools/Data required to conduct fast curve/definite-time studies:

i) Redflag(B322)/Arcflash circuit master list.
ii) Emaps and MDI to determine circuit configuration.
iii) Spreadsheet containing AR fault duties.
iv) Circuit breaker Interrupting Times.

Page 1 | 2

Rev 0: 7/17/2018

Fast Curve/Definite-Time Settings for Distribution Station Line Circuit Breakers



Page 2 | 2

Rev 0: 7/17/2018

APPENDIX B – CIRCUIT COVERAGE BY RELAY

Table B-1 – Fast Curve Settings Evaluation				
Substation	Circuit	Relay ID	Phase Coverage (%)	Ground Coverage (%)
[redacted]				

Table B-1 – Fast Curve Settings Evaluation				
Substation	Circuit	Relay ID	Phase Coverage (%)	Ground Coverage (%)

[redacted]

APPENDIX C – CIRCUIT COVERAGE TABLE

Table C-1 – Fast Curve Protection Circuit Coverage					
Substation	Circuit	Total Phase Length (ft)	Phase Coverage (%)	Total Ground Length (ft)	Ground Coverage (%)
[redacted]					

APPENDIX D – FAST CURVE SETTINGS

Table D-1 – Fast Curve Settings						
Substation	Circuit	Relay ID	TOC Minimum Trip Setting		Fast Curve Setting	
			Phase (A)	Ground (A)	Phase (A)	Ground (A)
[redacted]						

Table D-1 – Fast Curve Settings						
Substation	Circuit	Relay ID	TOC Minimum Trip Setting		Fast Curve Setting	
			Phase (A)	Ground (A)	Phase (A)	Ground (A)
[redacted]						

* Fast Curve setting not enabled for the relay.

APPENDIX E – EXISTING SETTINGS MINIMUM TRIP RANGE FIGURES

[redacted]

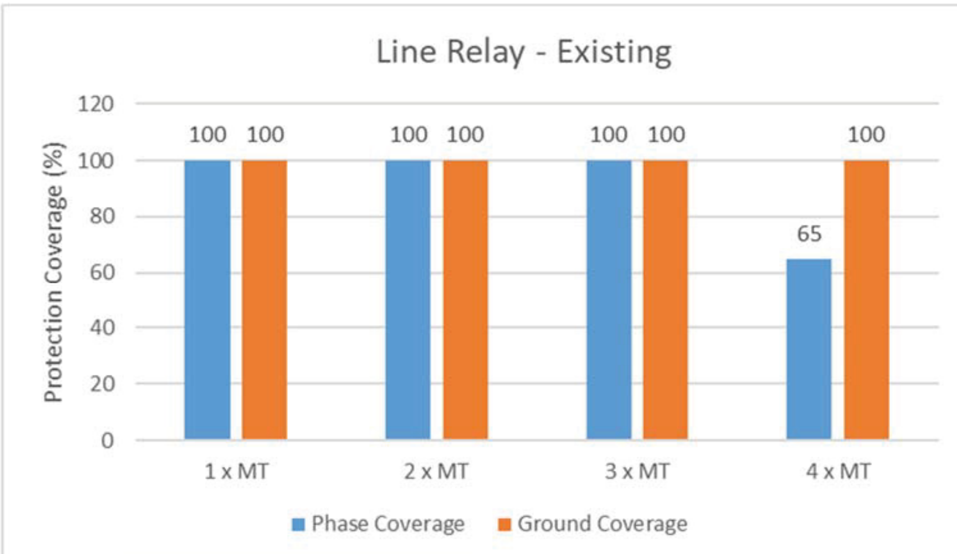


Figure E-1 – [redacted] Existing Line Coverage

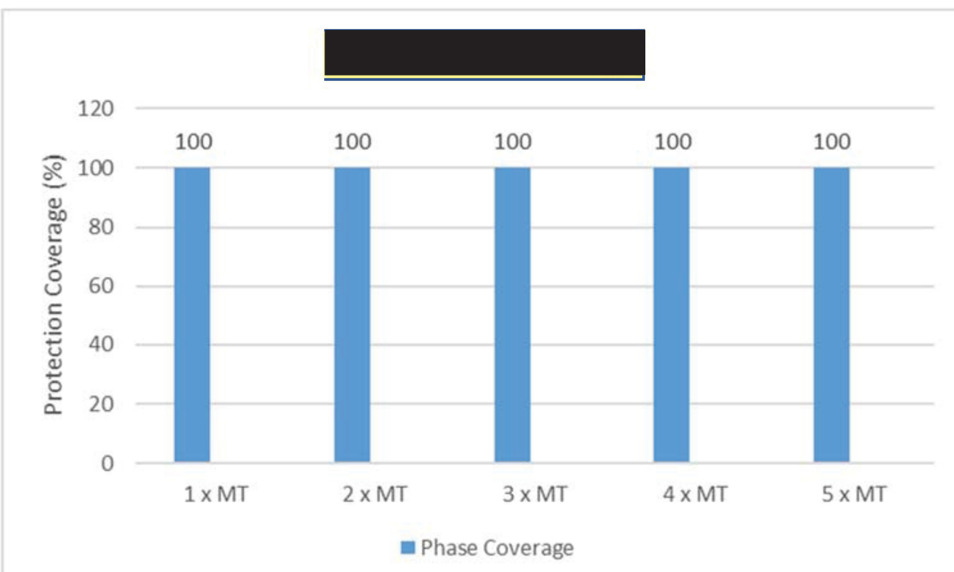


Figure E-2 – [redacted] Coverage

[redacted]

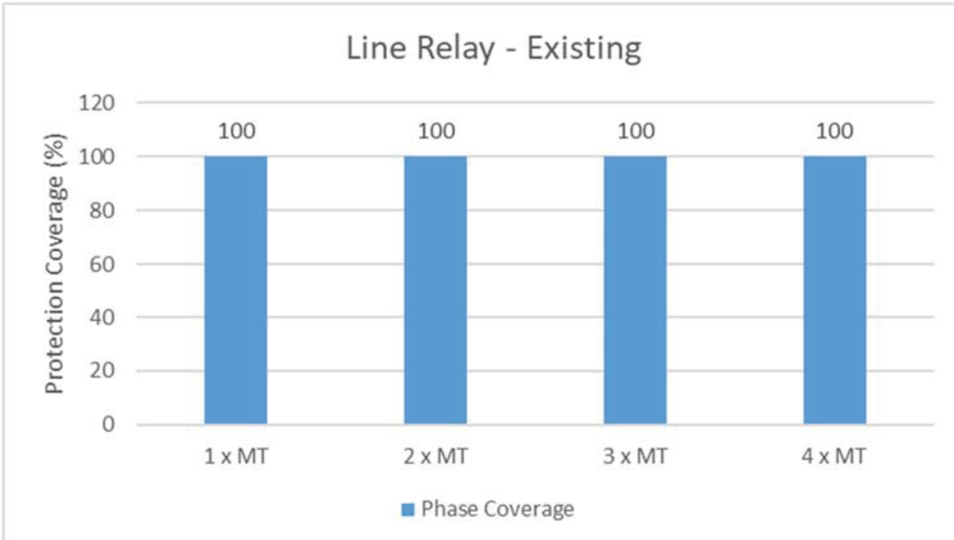


Figure E-3 – [redacted] Existing Line Coverage

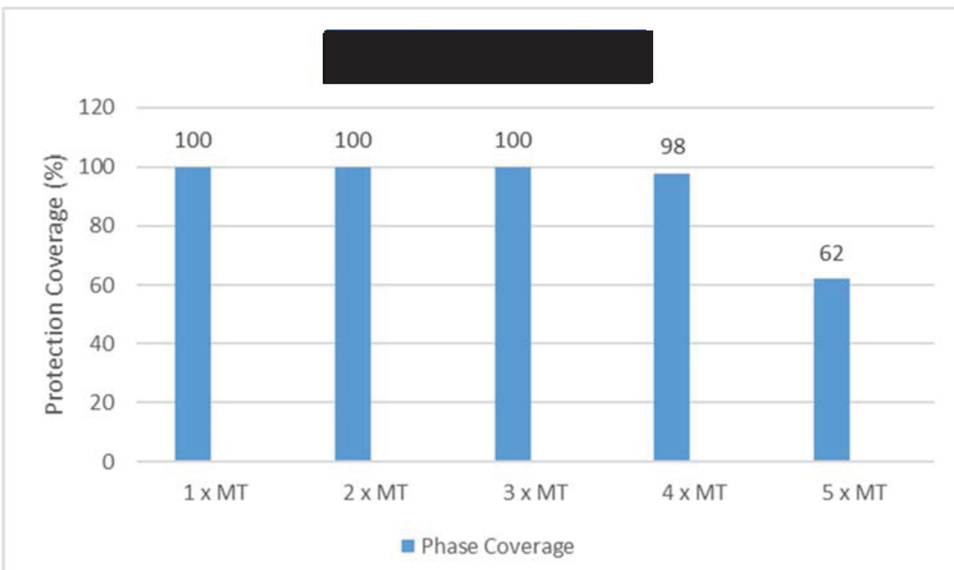


Figure E-4 – [redacted] Coverage

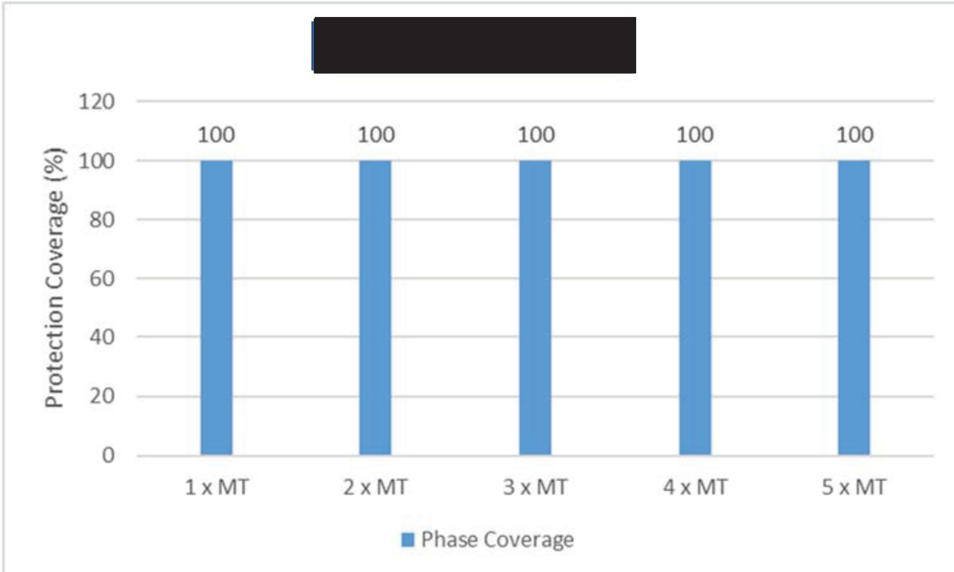


Figure E-5 – [redacted] Coverage

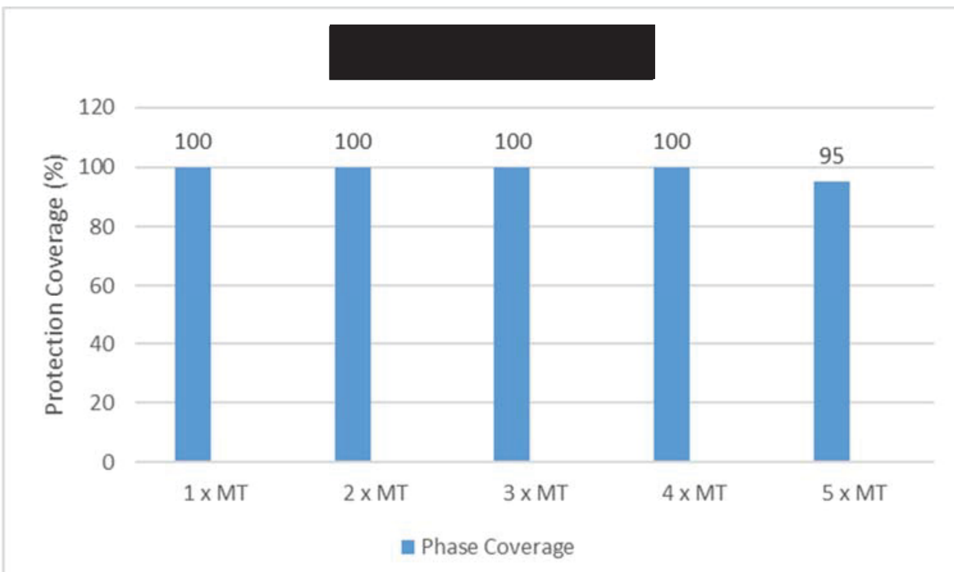


Figure E-6 – [redacted] Coverage

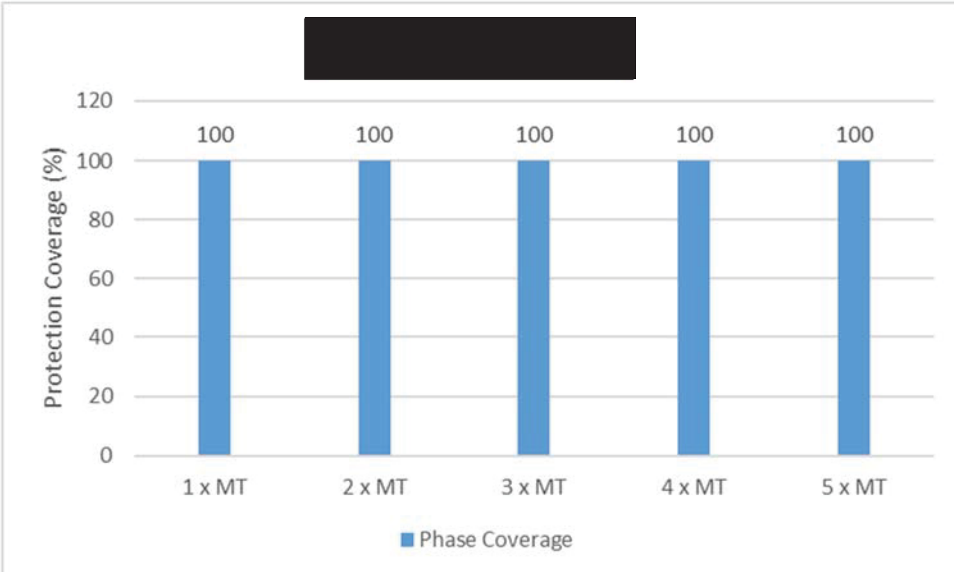


Figure E-7 – [redacted] Coverage

[redacted]

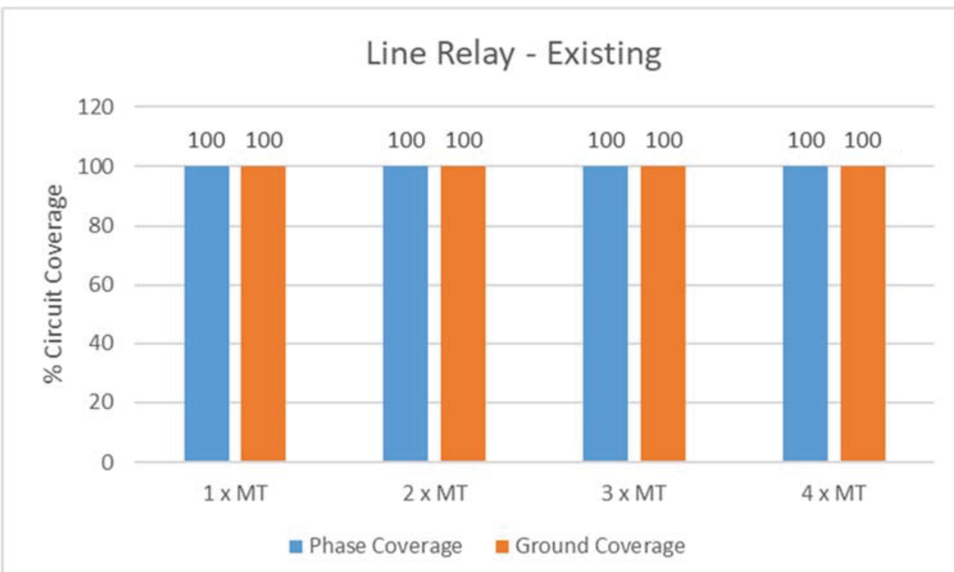


Figure E-8 – [redacted] Existing Line Coverage

[redacted]

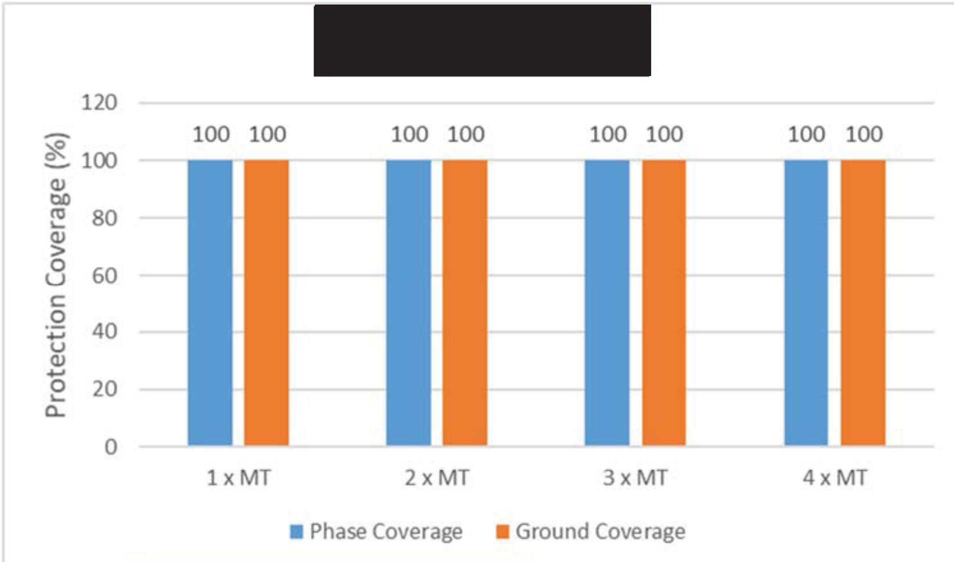


Figure E-9 – [redacted] Existing Line Coverage

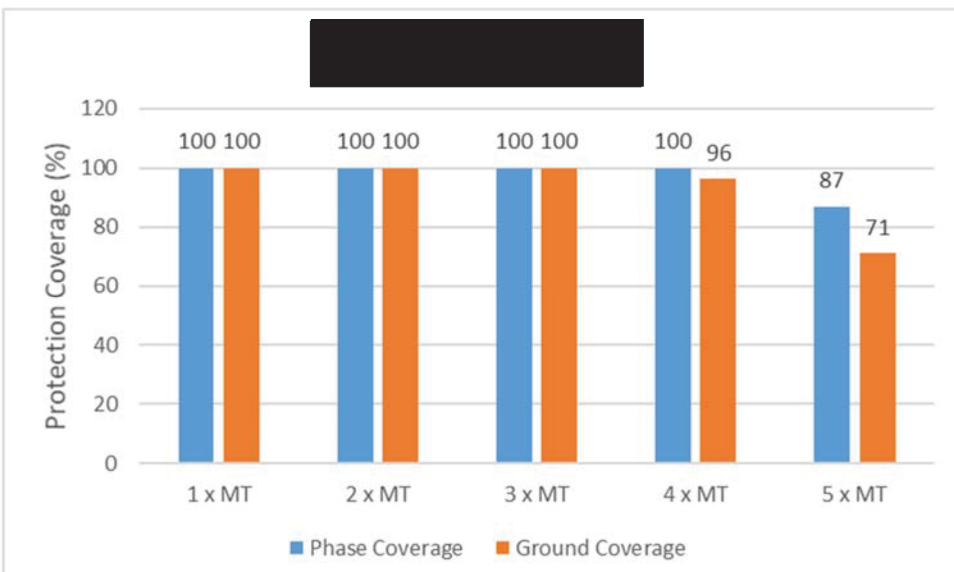


Figure E-10 – [redacted] Coverage

[redacted]

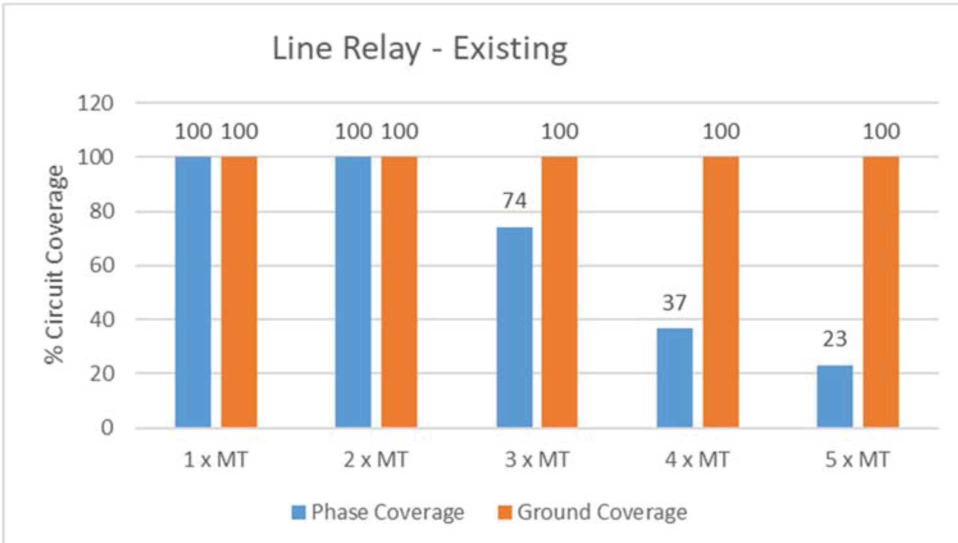


Figure E-11 – [redacted] Existing Line Coverage

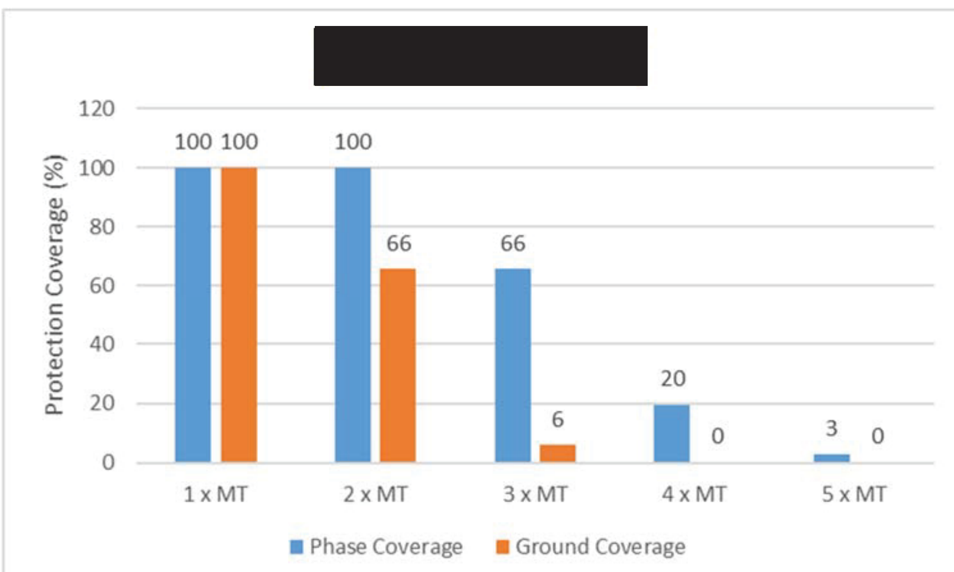


Figure E-12 – [redacted] Coverage

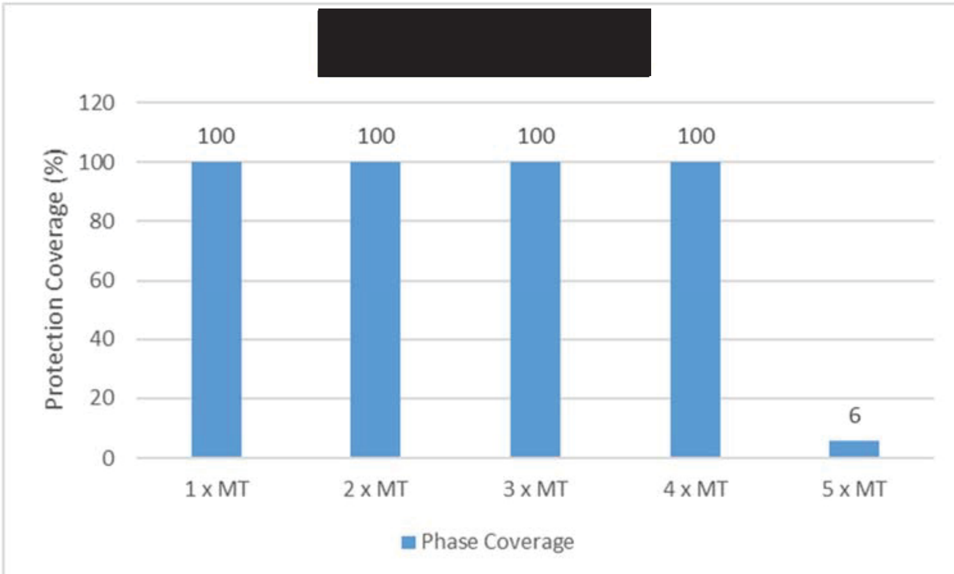


Figure E-13 – [redacted] Coverage

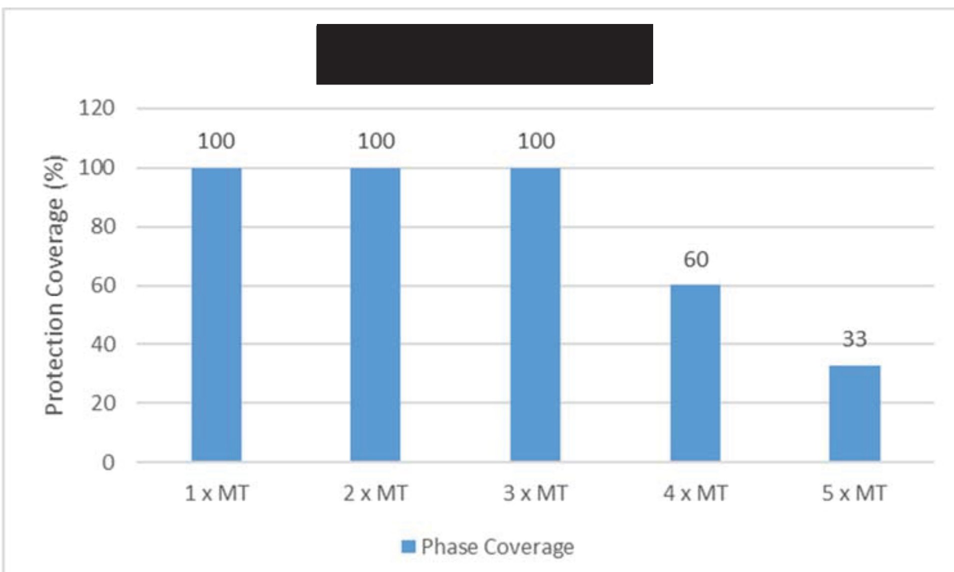


Figure E-14 – [redacted] Coverage

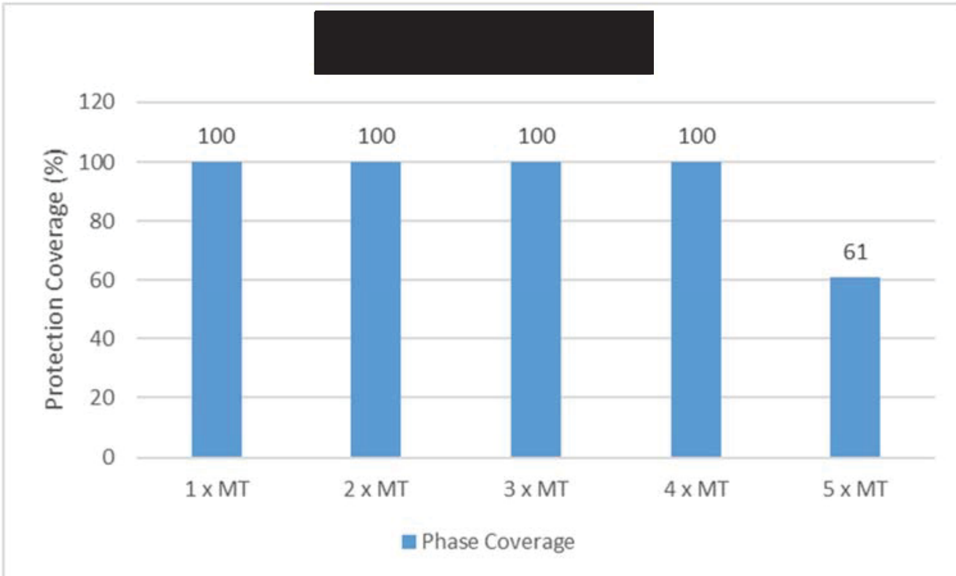


Figure E-15 – [redacted] Coverage

[redacted]

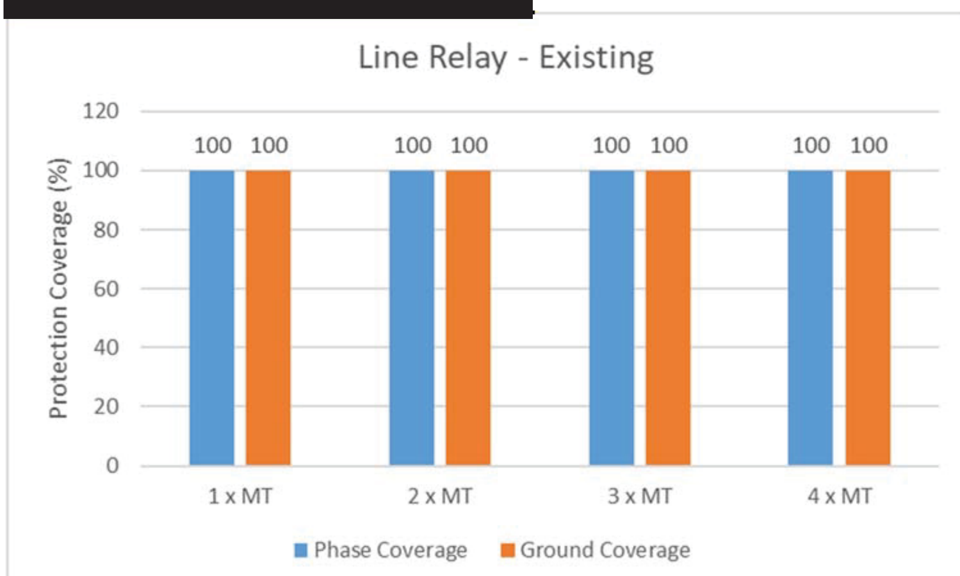


Figure E-16 [redacted] Existing Line Coverage

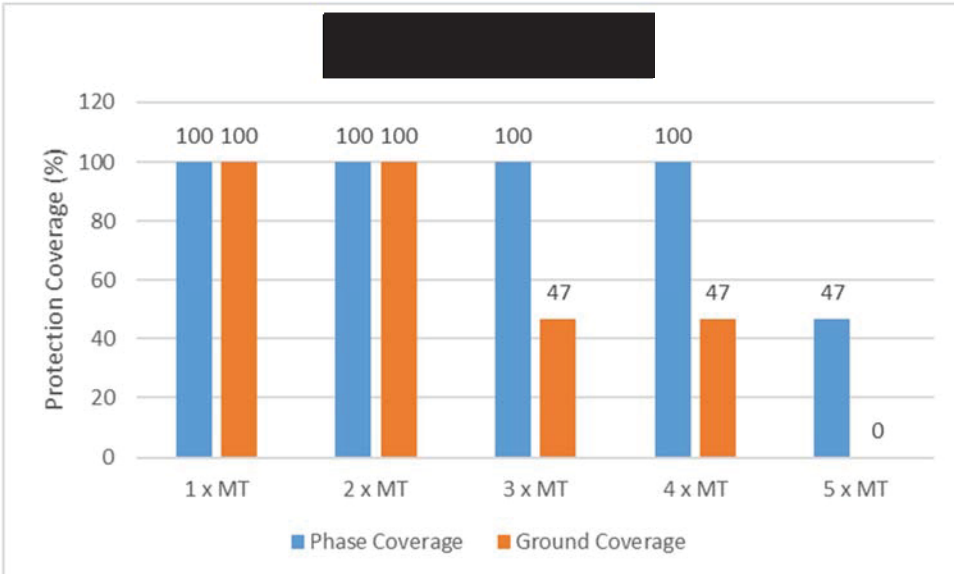


Figure E-17 – [redacted] Coverage

[redacted]

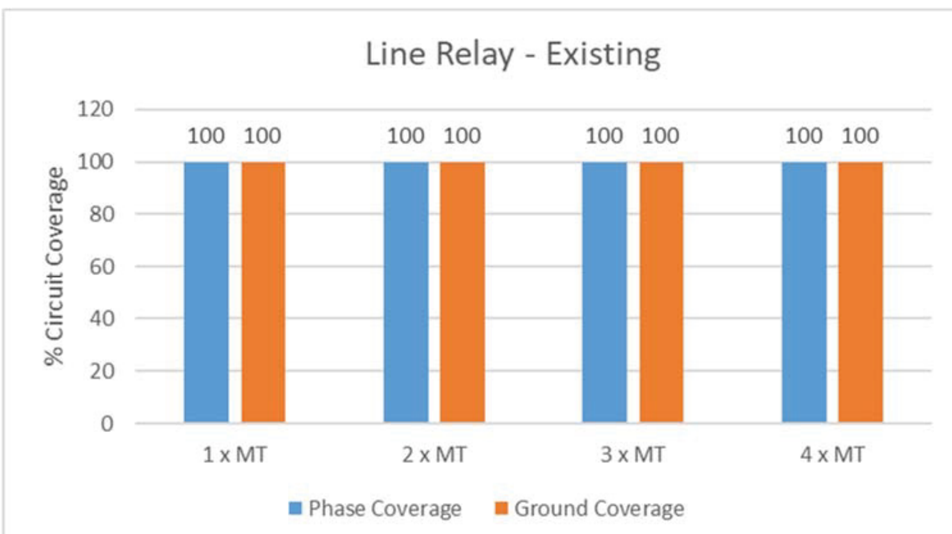


Figure E-18 – [redacted] Existing Line Coverage

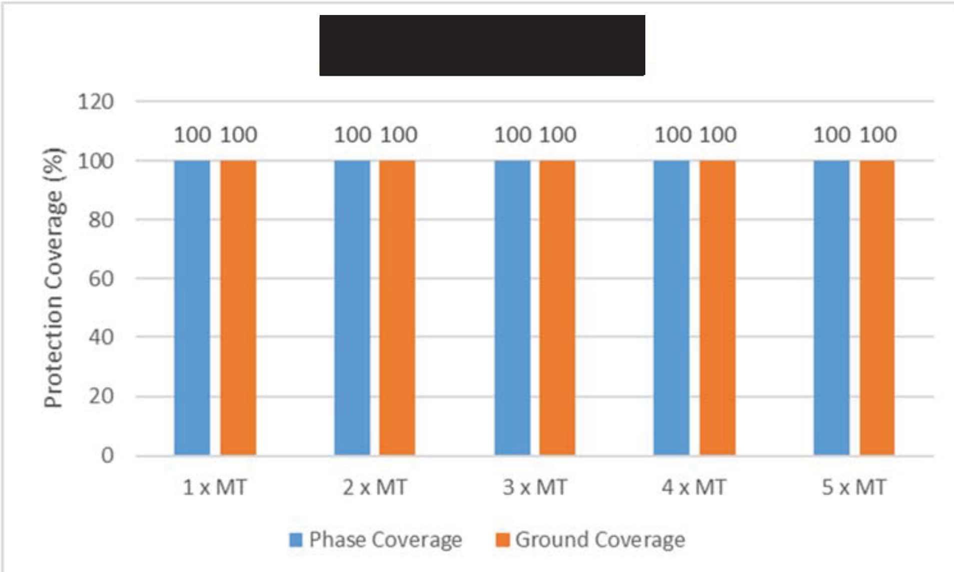


Figure E-19 – [redacted] Coverage

[redacted]

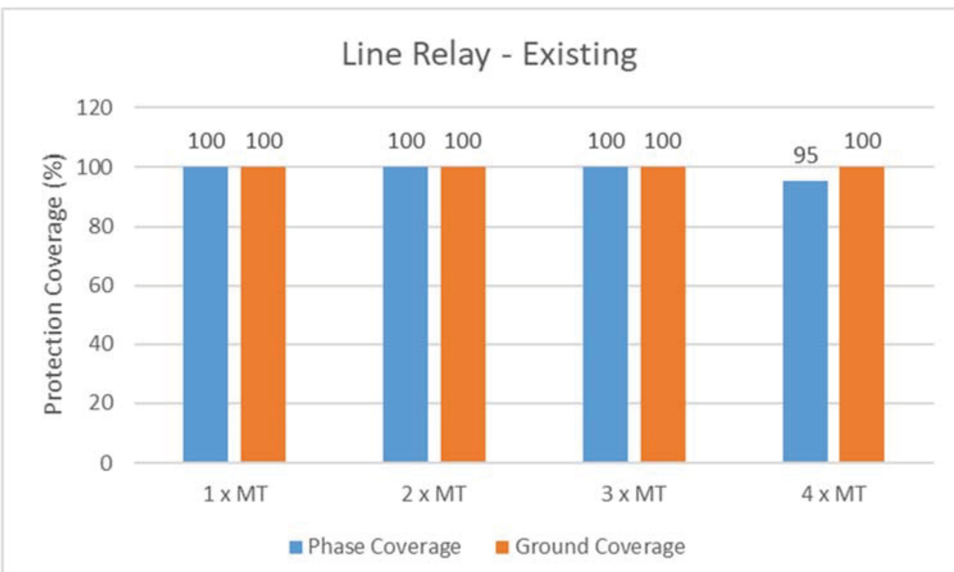


Figure E-20 – [redacted] Existing Line Coverage

[redacted]

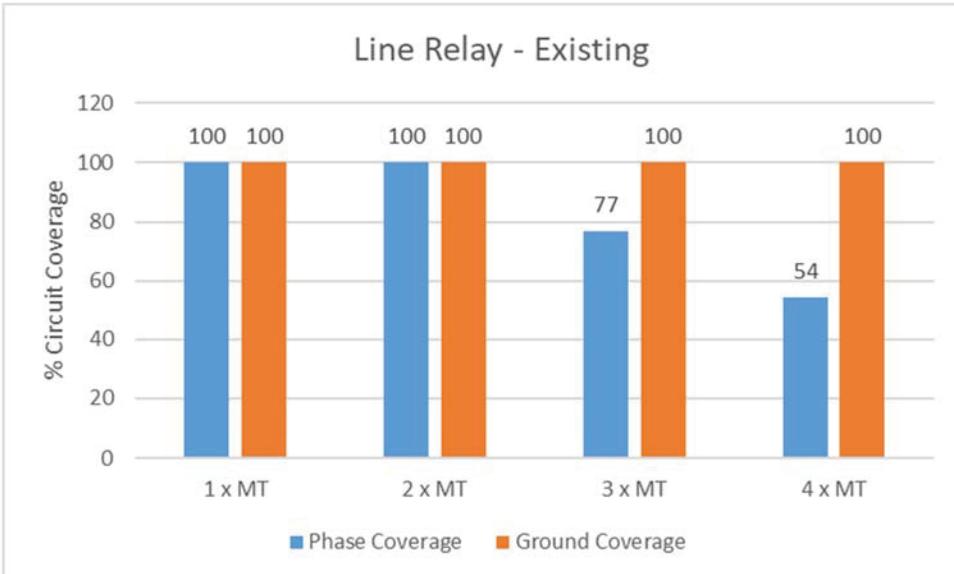


Figure E-21 – [redacted] Existing Line Coverage

[redacted]

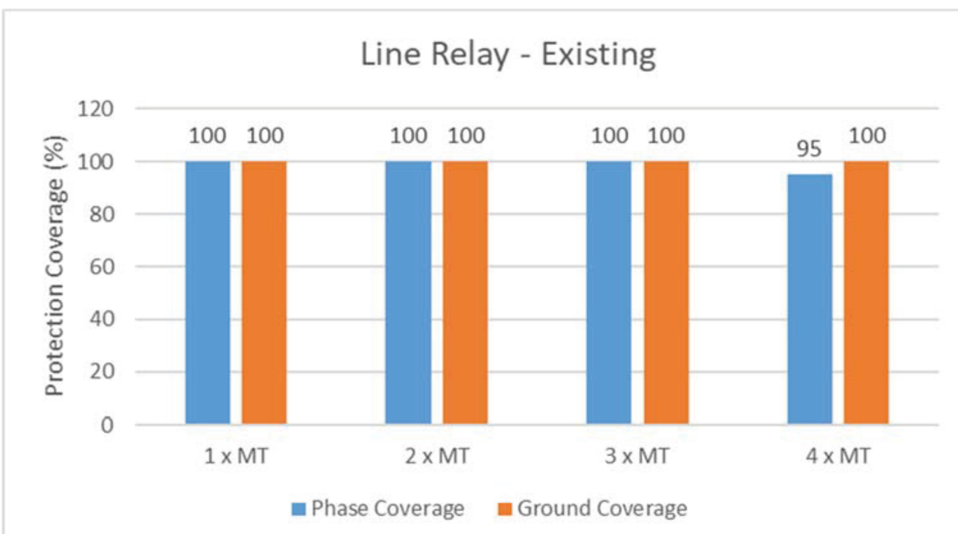


Figure E-22 – [redacted] Existing Line Coverage

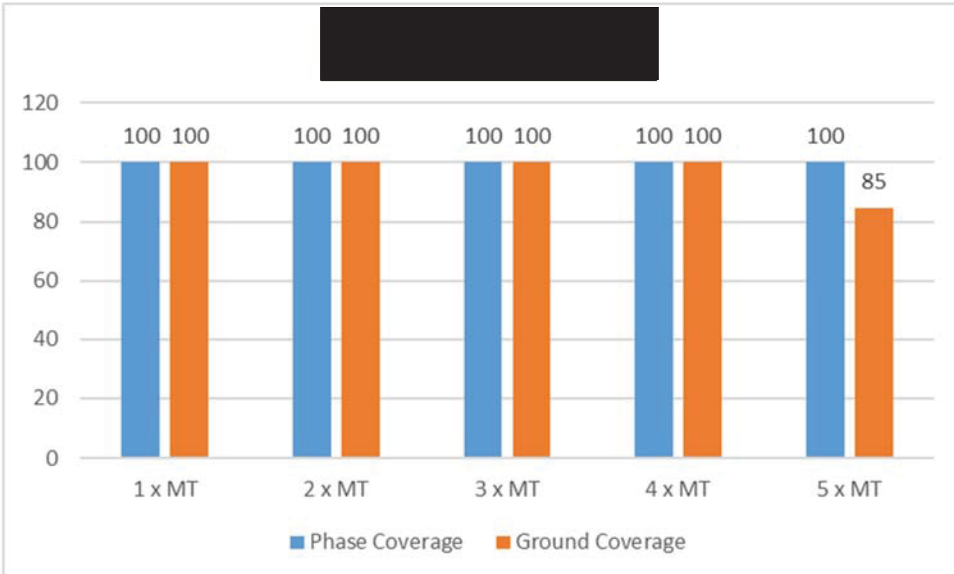


Figure E-23 – [redacted] Coverage

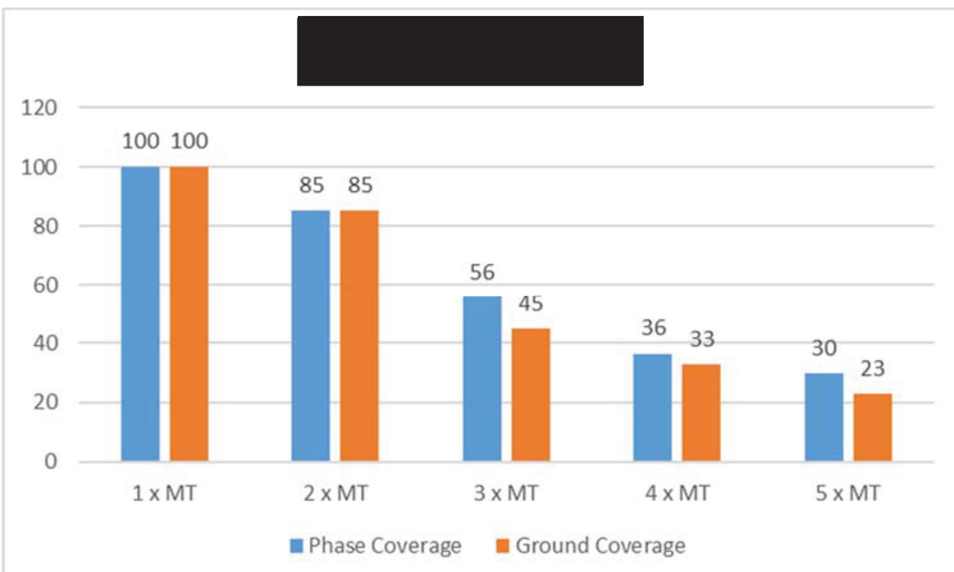


Figure E-24 – [redacted] Coverage

[redacted]

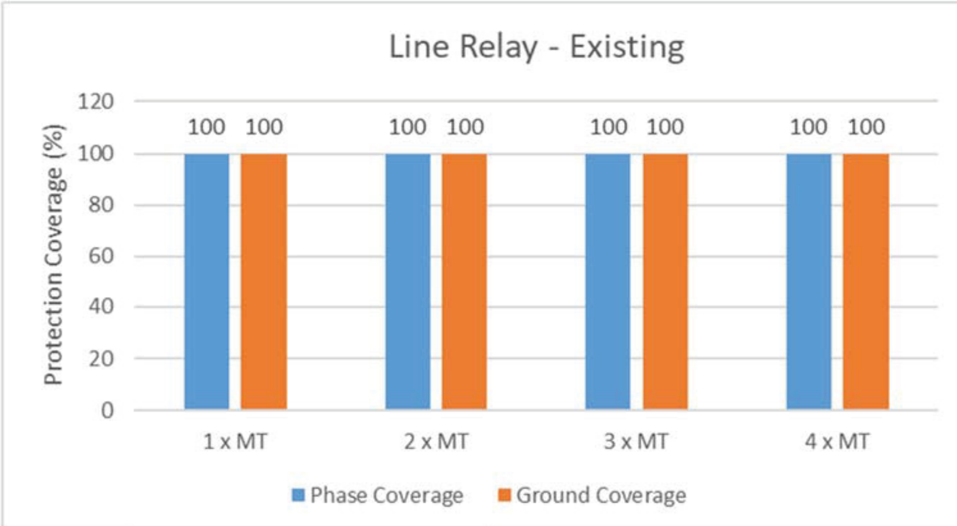


Figure E-25 – [redacted] Existing Line Coverage

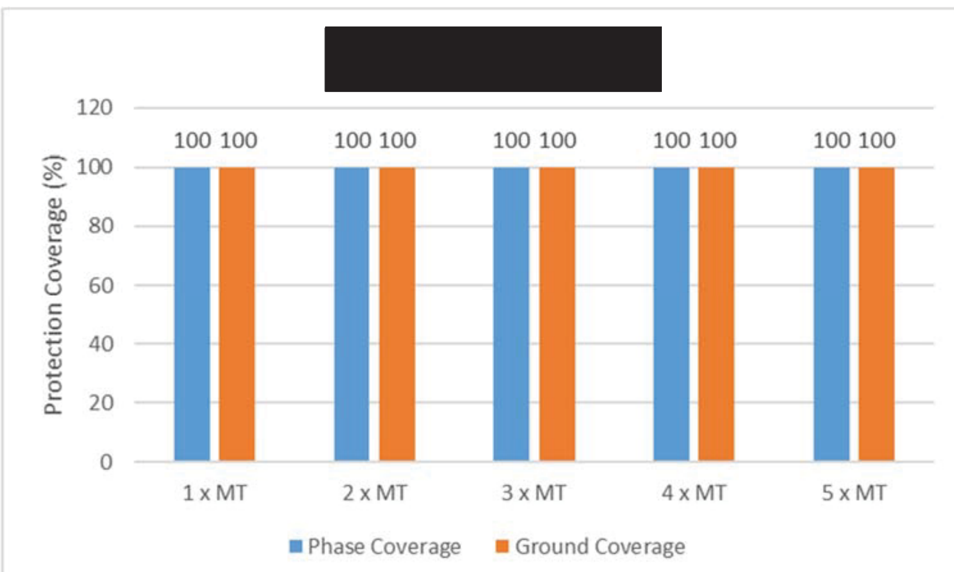


Figure E-26 [redacted] Coverage

[redacted]

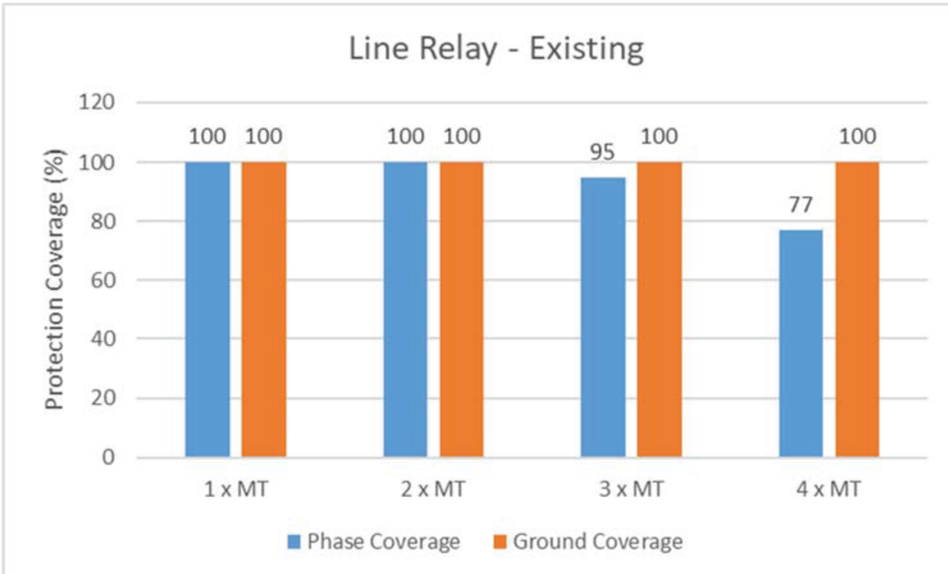


Figure E-27 – [redacted] Existing Line Coverage

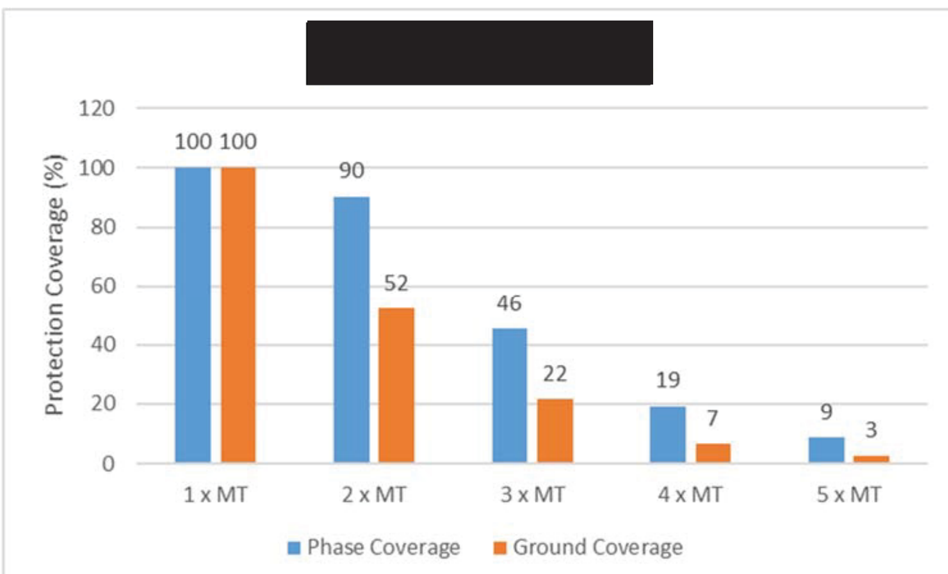


Figure E-28 – [redacted] Coverage

[redacted]

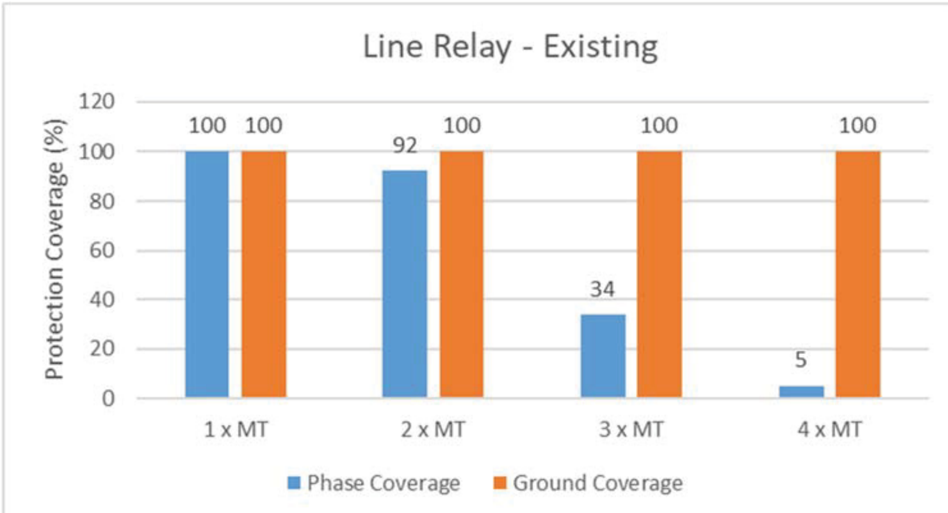


Figure E-29 [redacted] Existing Line Coverage

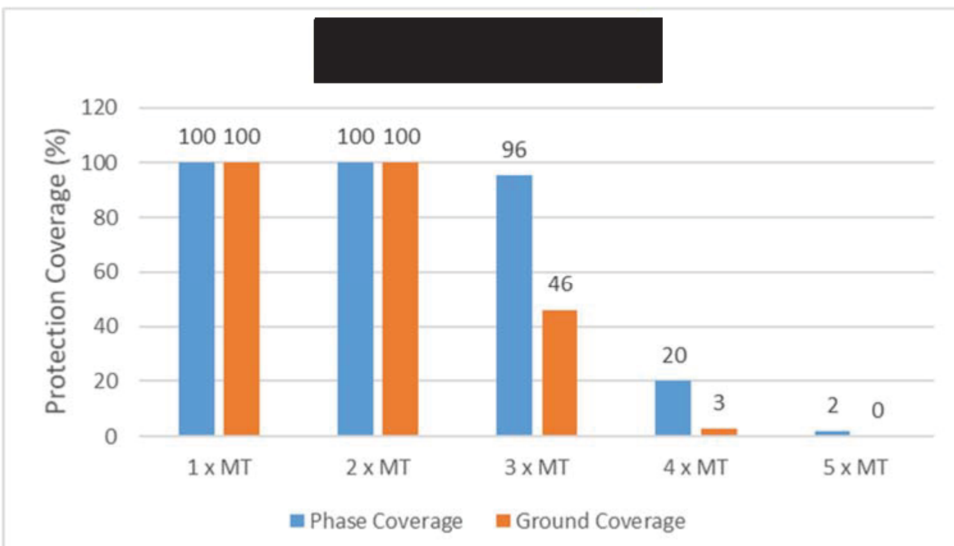


Figure E-30 – [redacted] Coverage

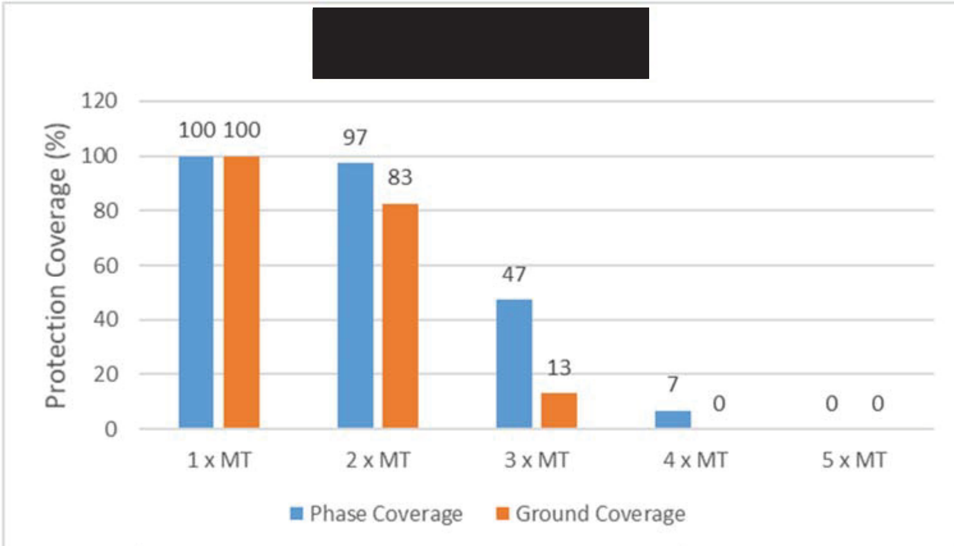


Figure E-31 – [redacted] Coverage

[redacted]

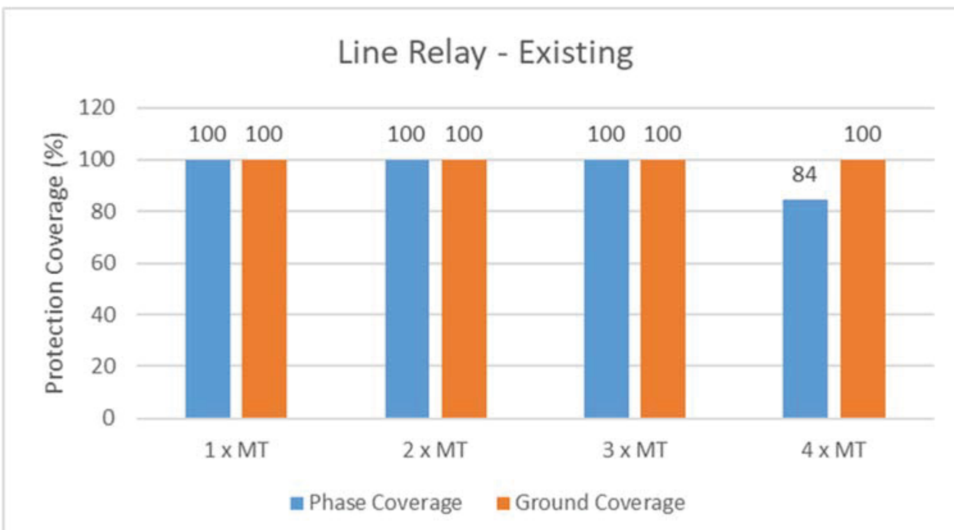


Figure E-32 – [redacted] Existing Line Coverage

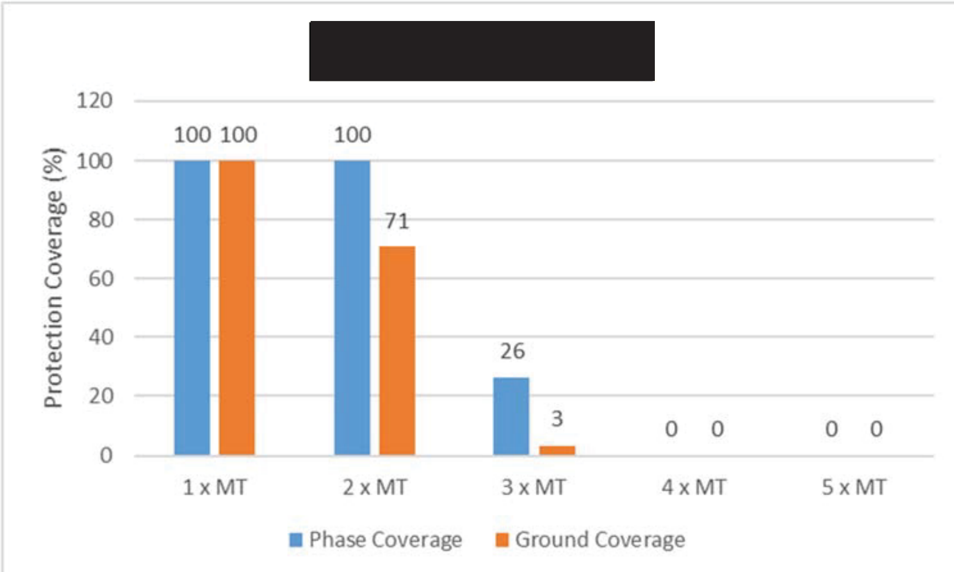


Figure E-33 – [redacted] Coverage

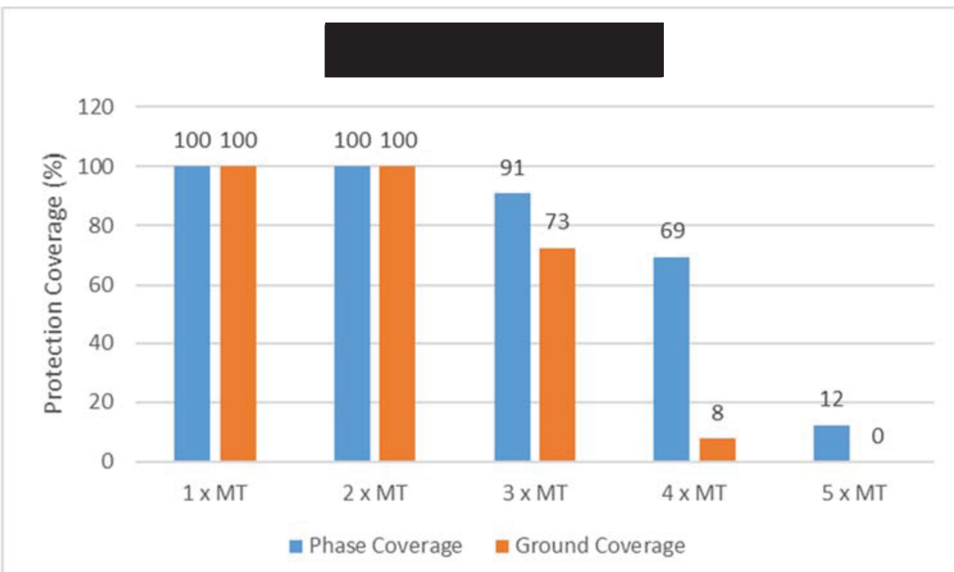


Figure E-34 – [redacted] Coverage

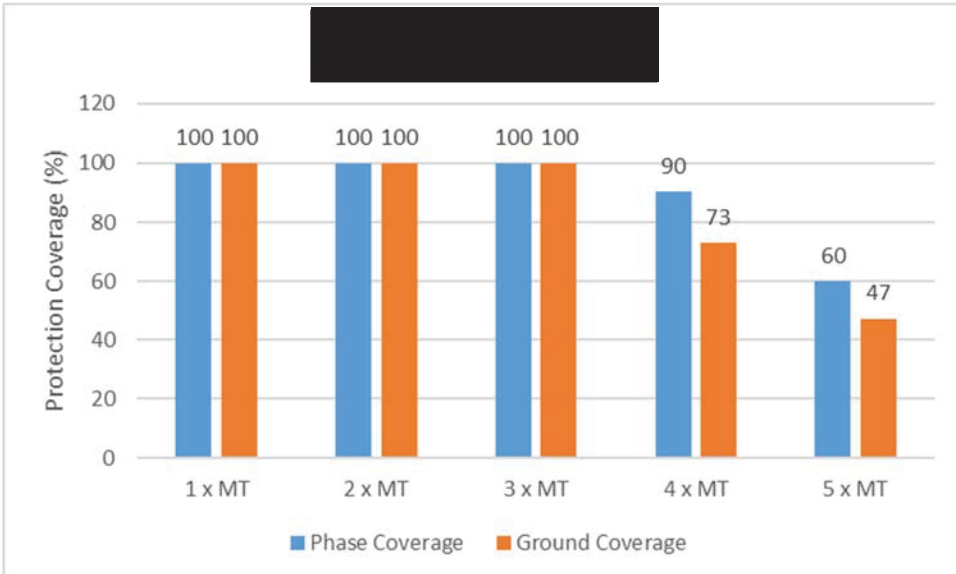


Figure E-35 – [redacted] Coverage

[redacted]

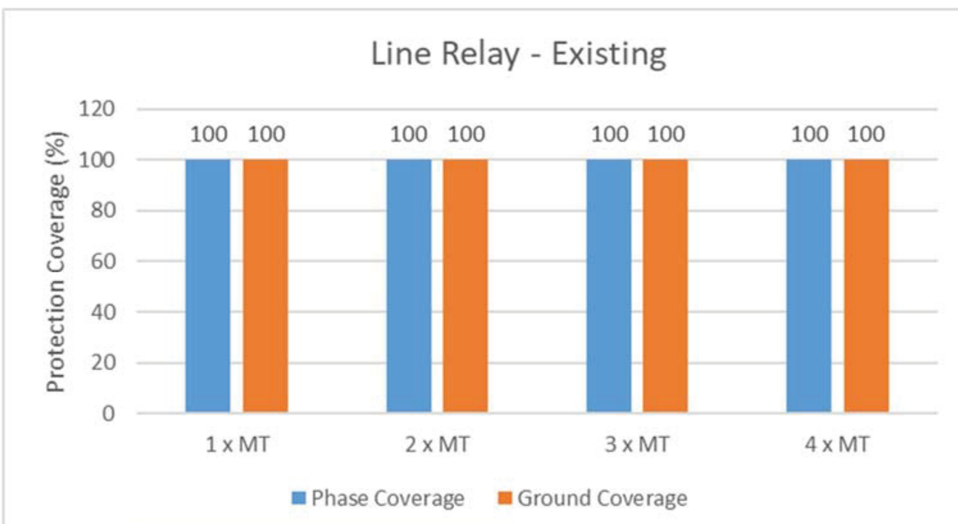


Figure E-36 – [redacted] Existing Line Coverage

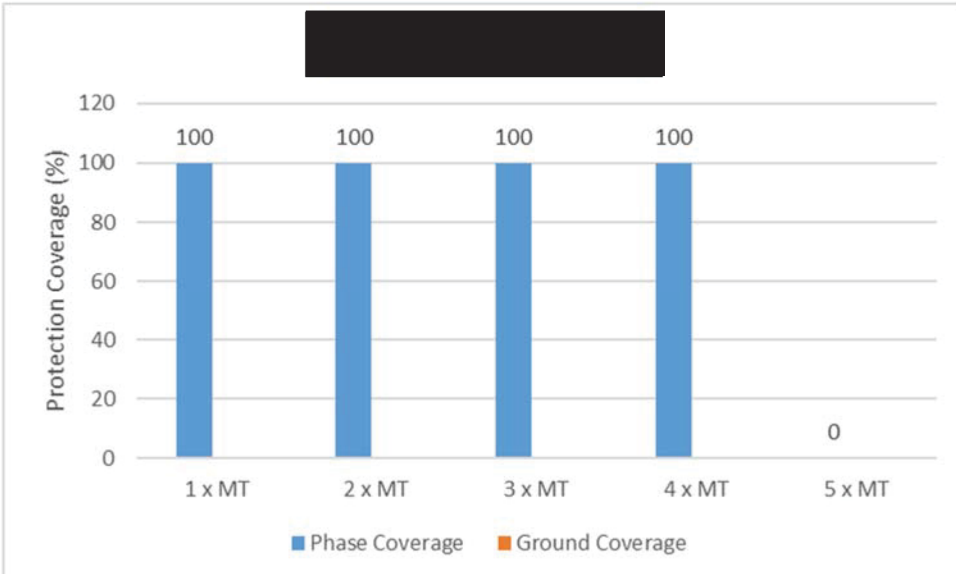


Figure E-37 – [redacted] Coverage

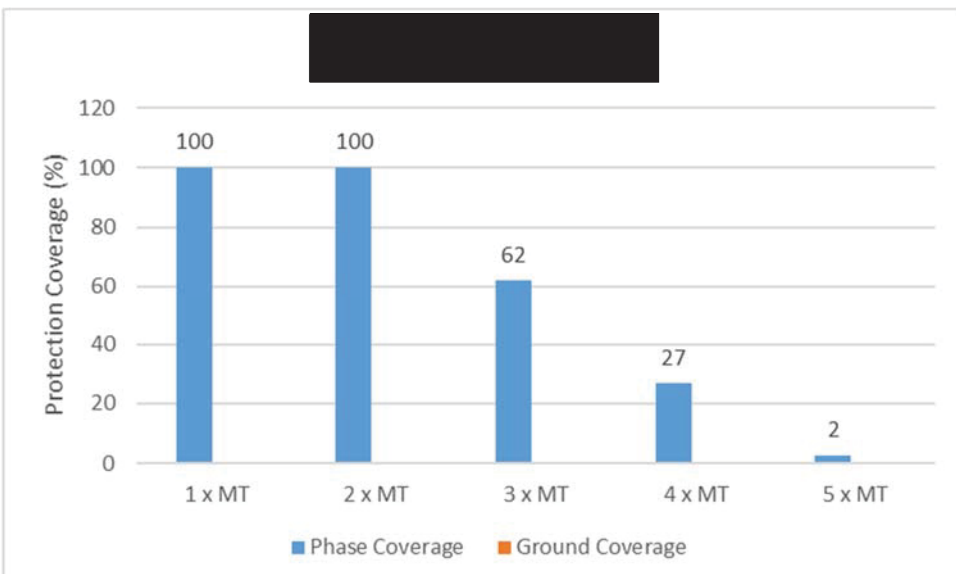


Figure E-38 – [redacted] Coverage

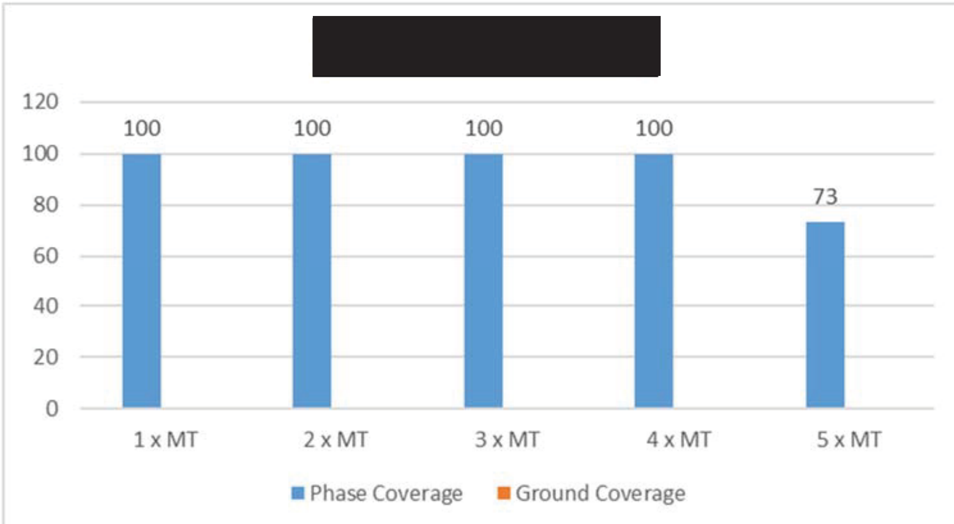


Figure E-39 – [redacted] Coverage

APPENDIX F – RECOMMENDED SETTINGS MINIMUM TRIP RANGE FIGURES

[redacted]

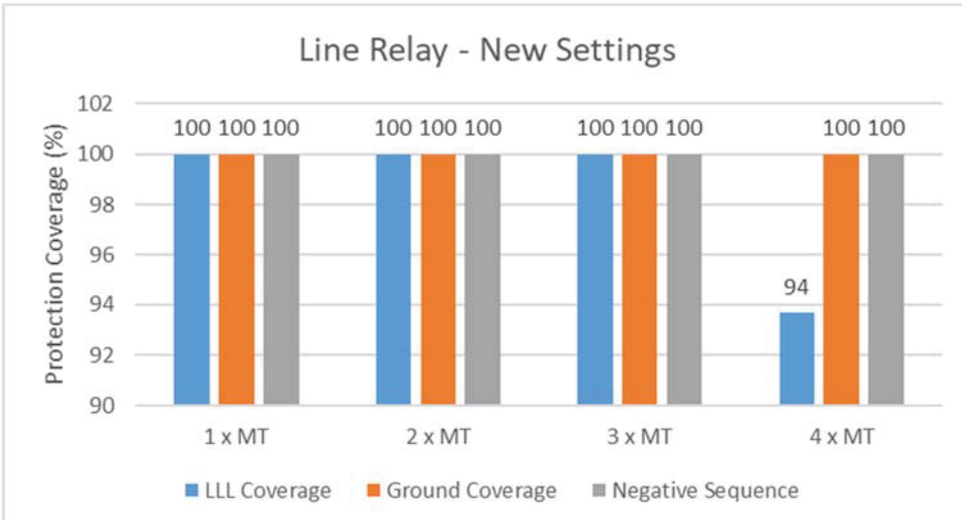


Figure F-1 [redacted] Recommended Line Coverage

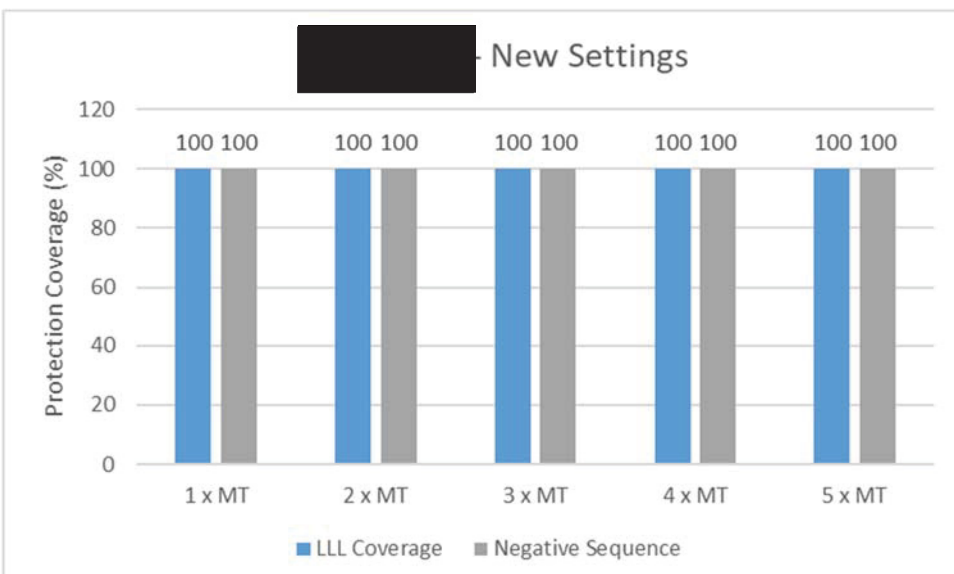


Figure F-2 – [redacted] Coverage

[redacted]

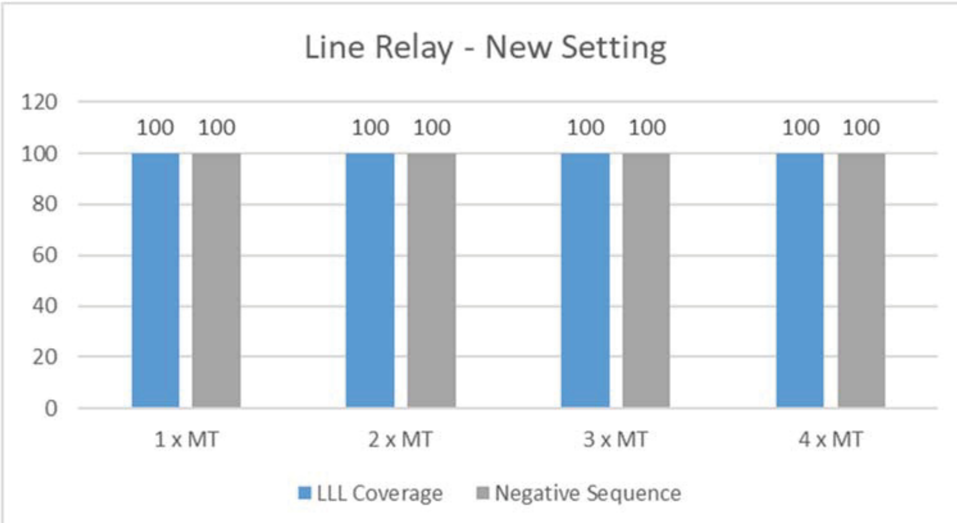


Figure F-3 [redacted] Recommended Line Coverage

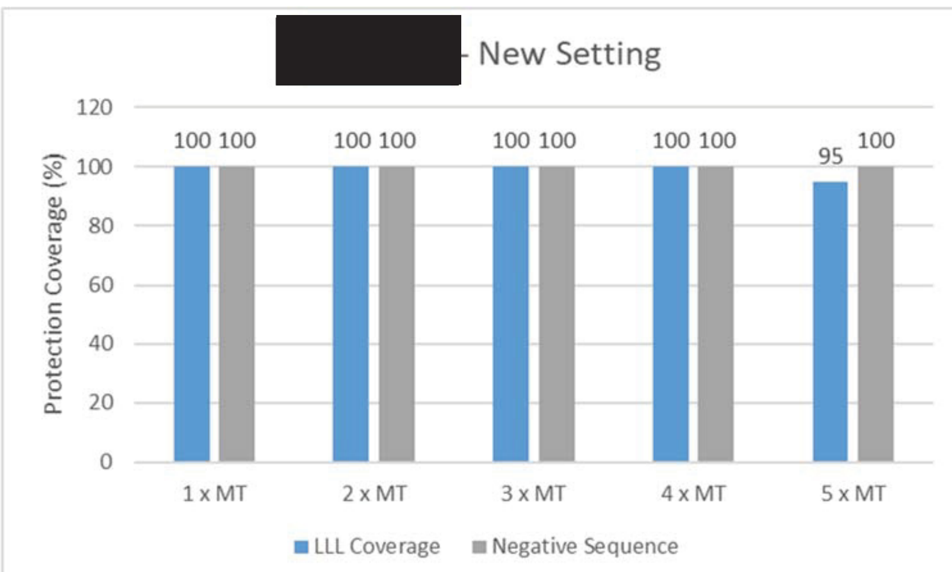


Figure F-4 – [redacted] Coverage

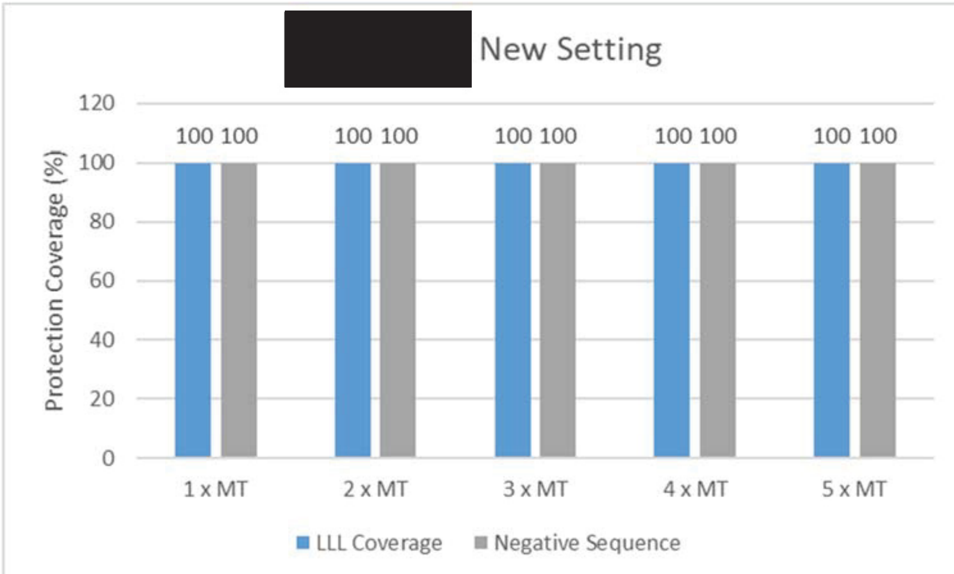


Figure F-5 – [redacted] Coverage

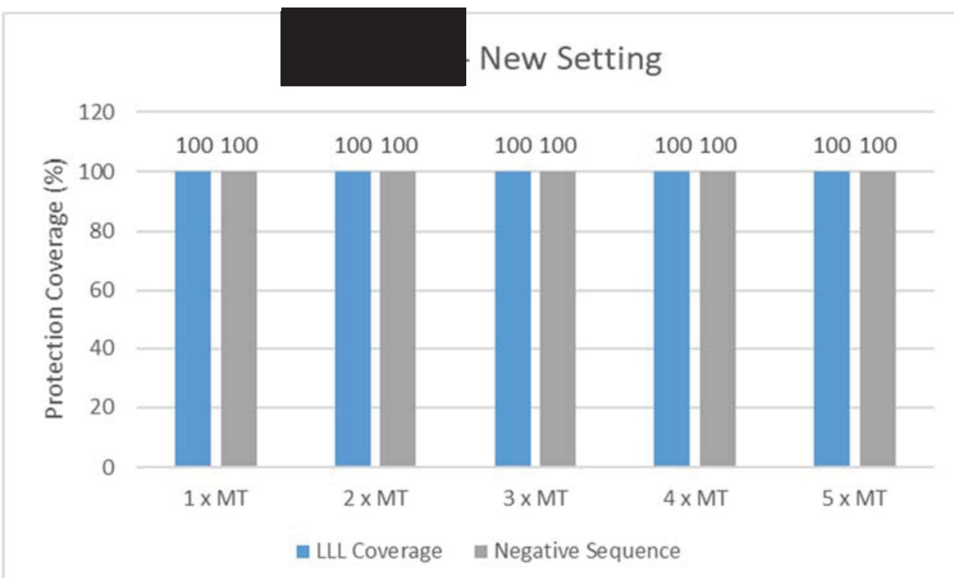


Figure F-6 – [redacted] Coverage

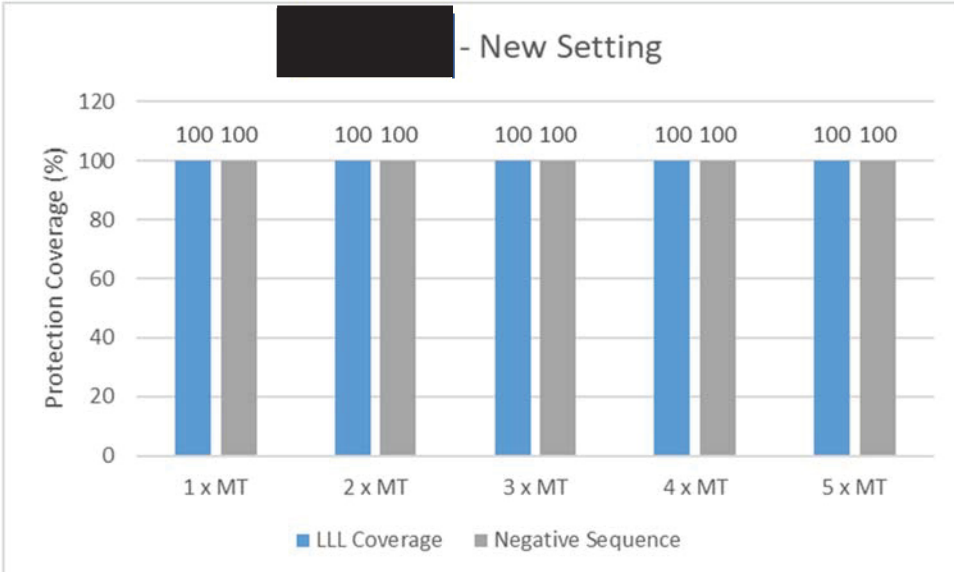


Figure F-7 [redacted] Coverage

[redacted]

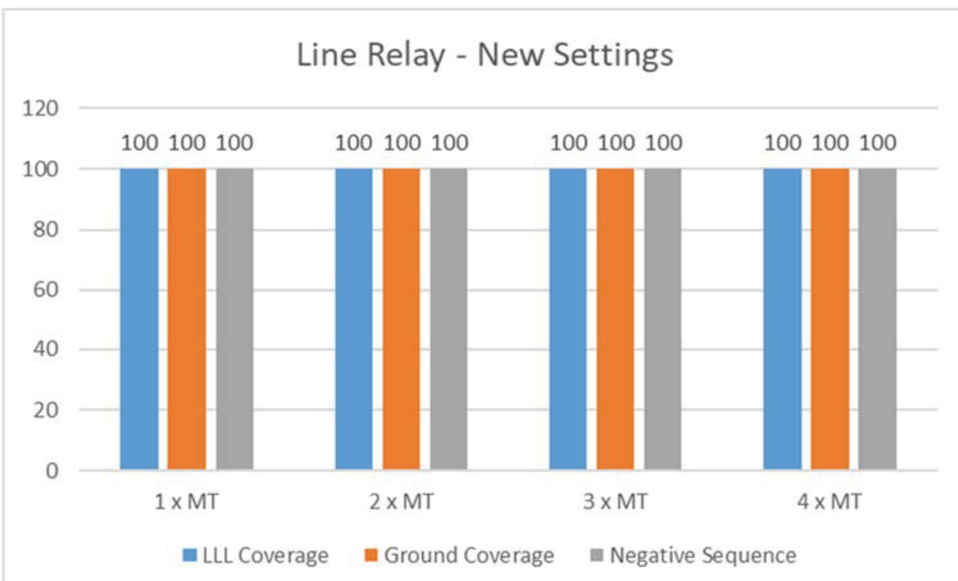


Figure F-8 – [redacted] Recommended Line Coverage

[redacted]

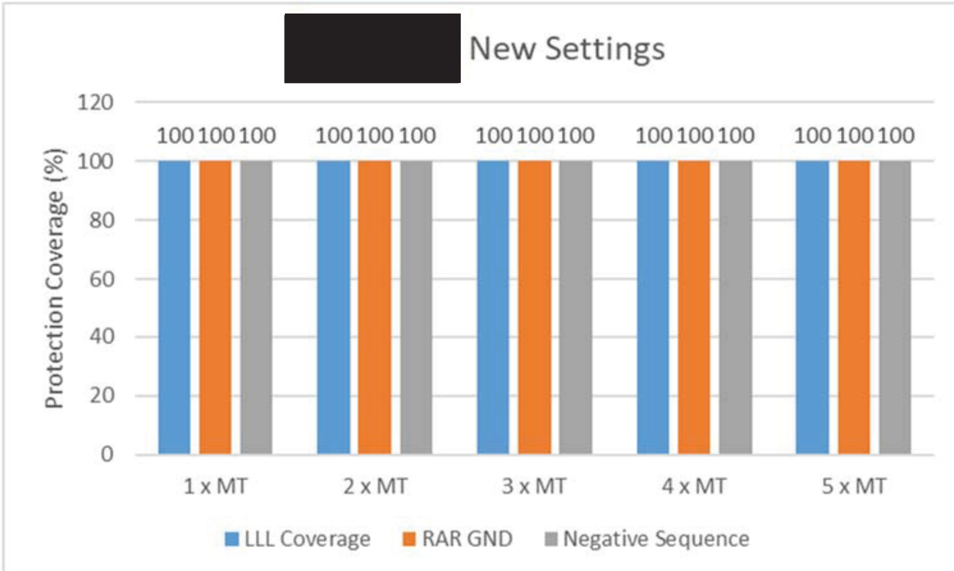


Figure F-9 – [redacted] Recommended Line Coverage

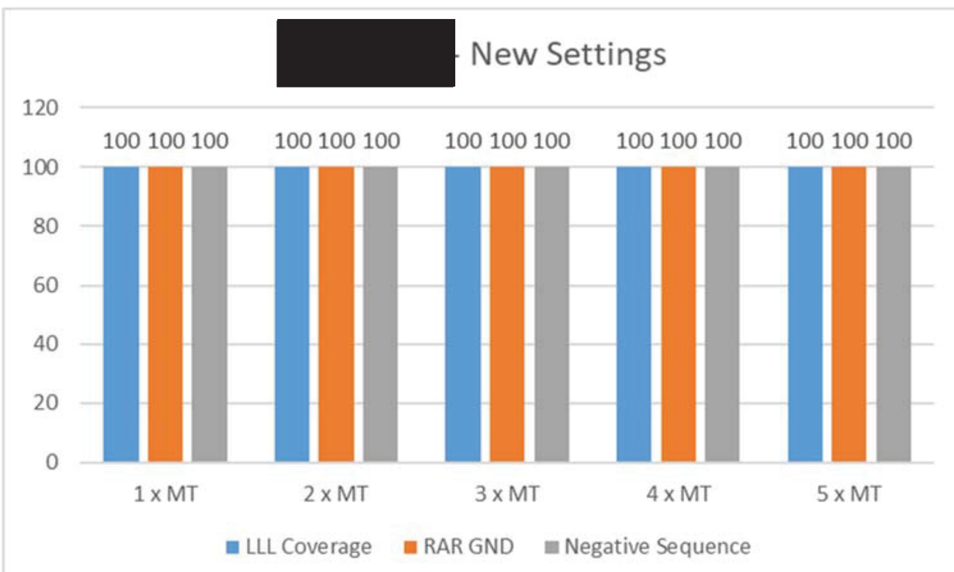


Figure F-10 [redacted] Coverage

[redacted]

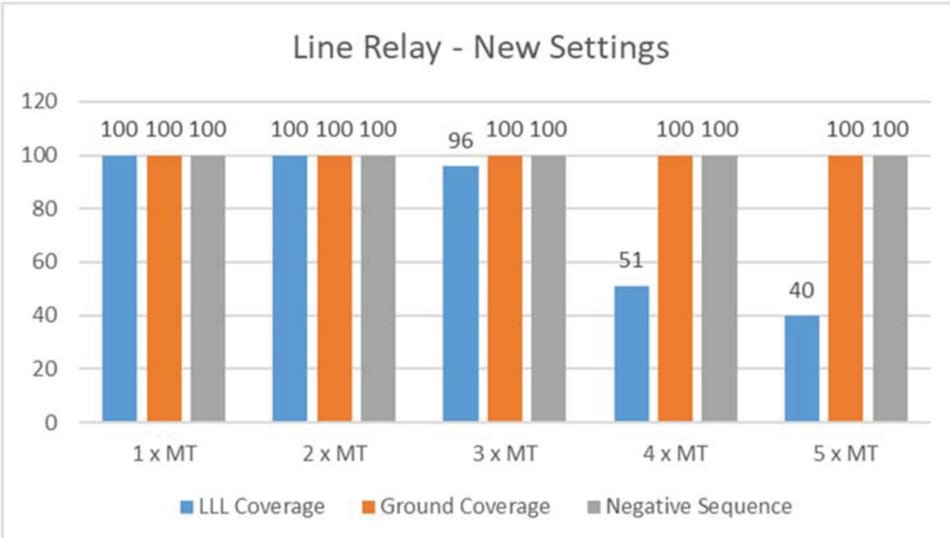


Figure F-11 – [redacted] Recommended Line Coverage

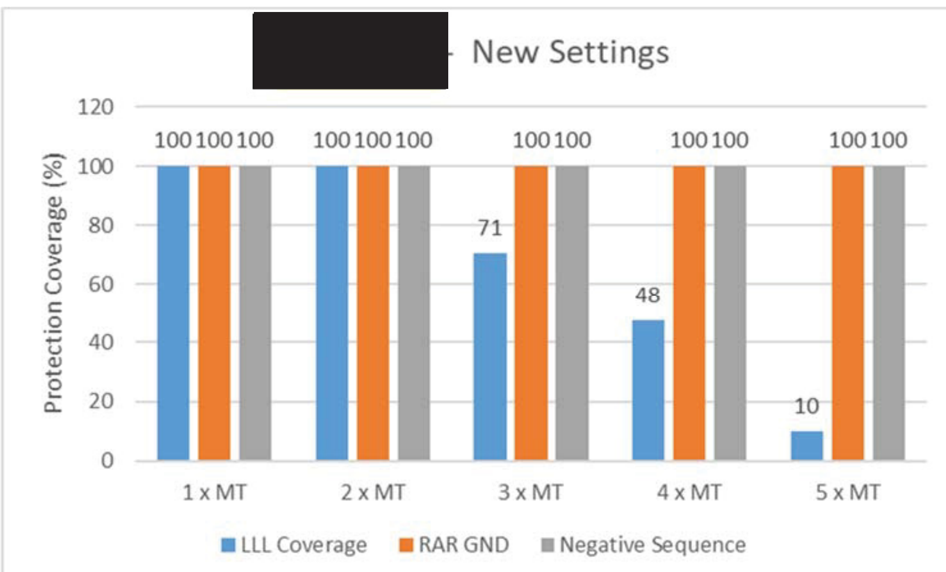


Figure F-12 – [redacted] Coverage

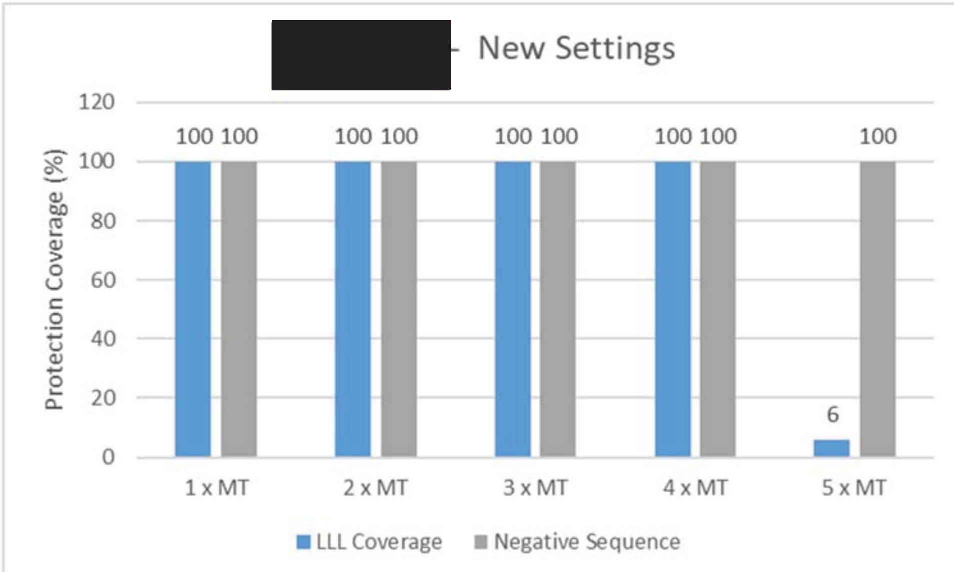


Figure F-13 – [redacted] Coverage

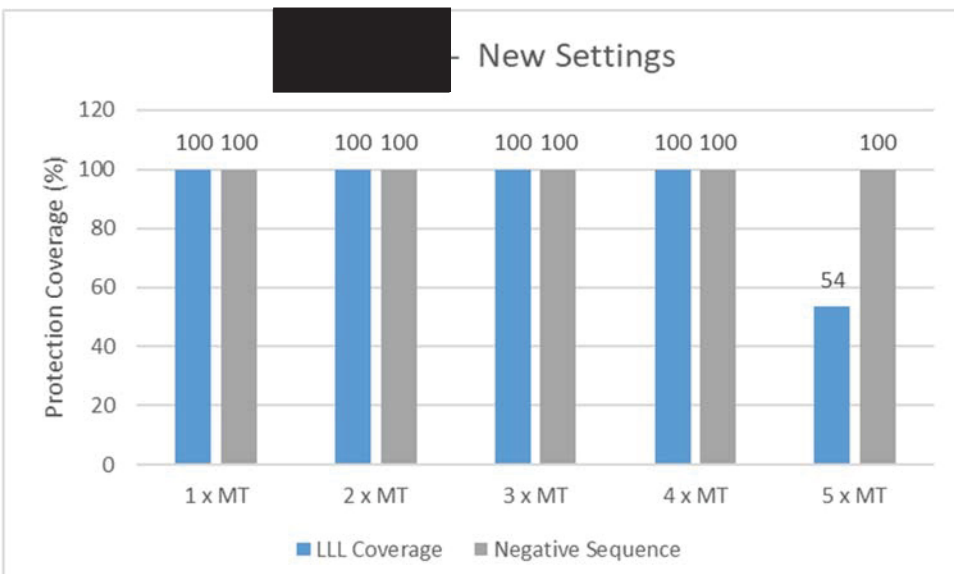


Figure F-14 – [redacted] Coverage

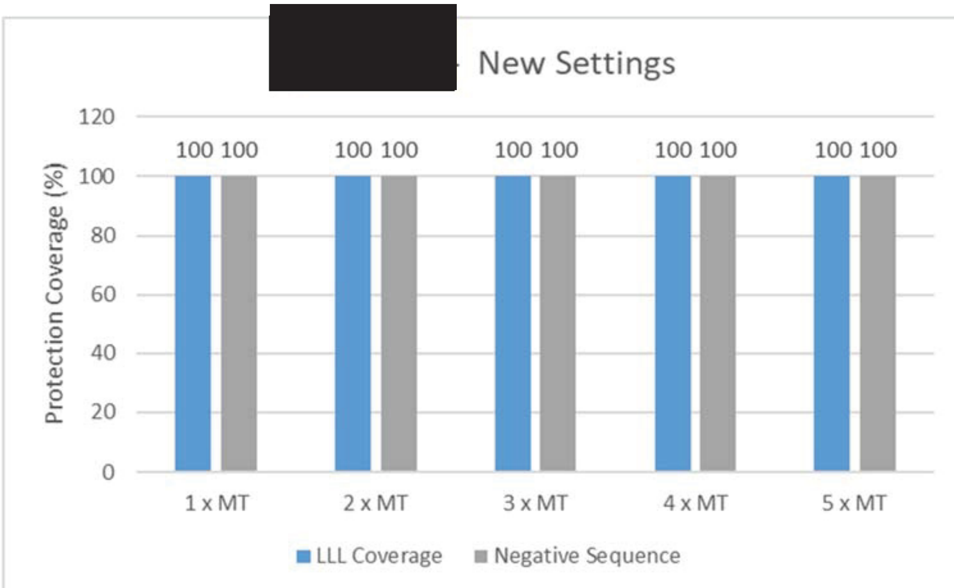


Figure F-15 – [redacted] Coverage

[redacted]

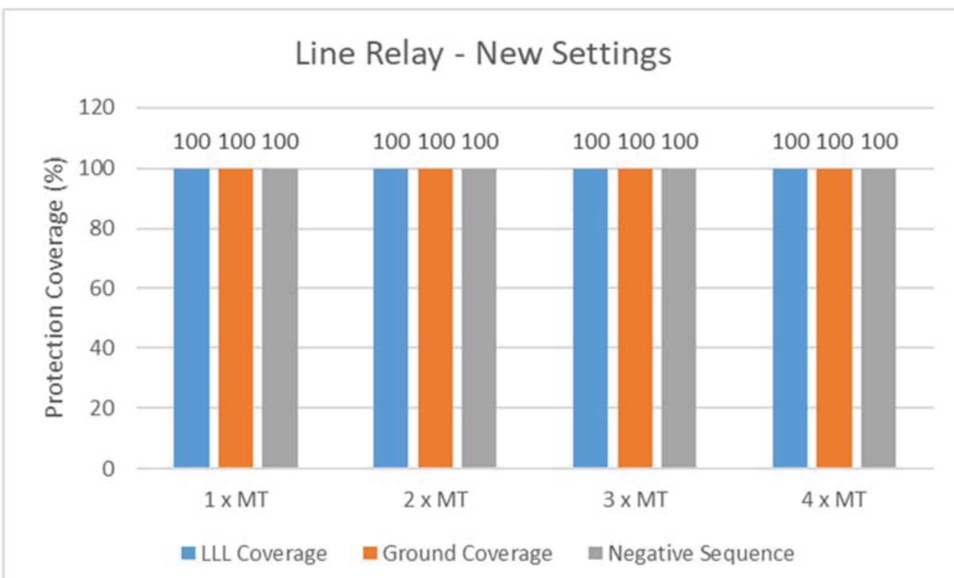


Figure F-16 [redacted] Recommended Line Coverage

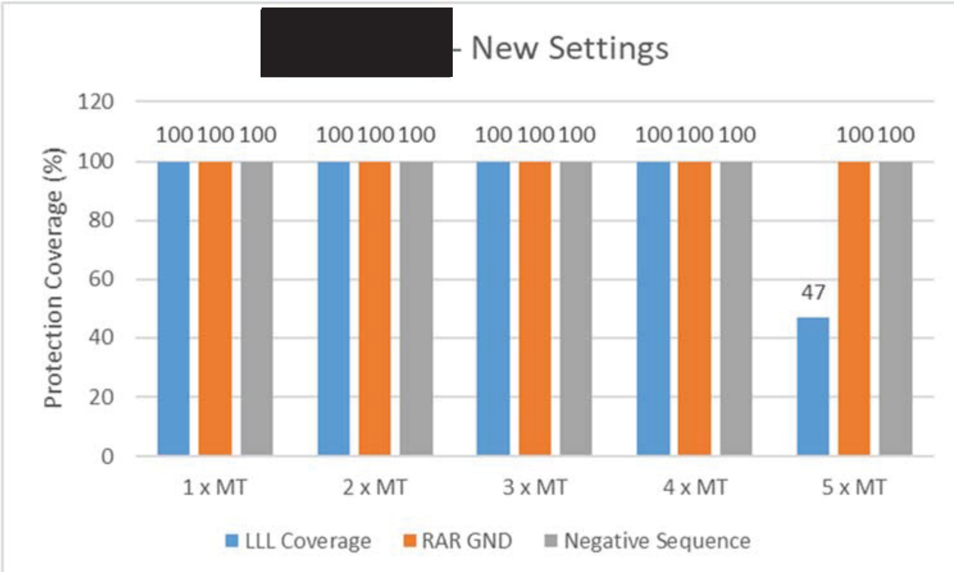


Figure F-17 – [redacted] Coverage

[redacted]

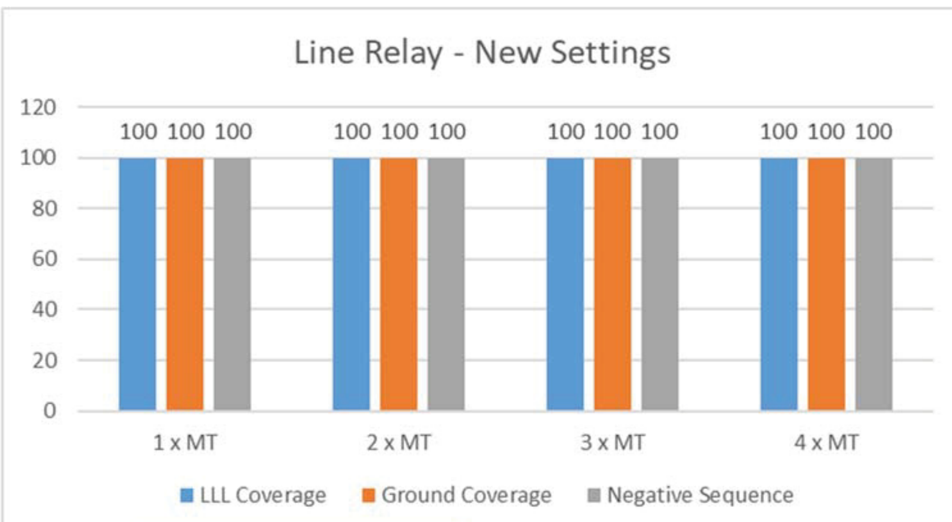


Figure F-18 – [redacted] Recommended Line Coverage

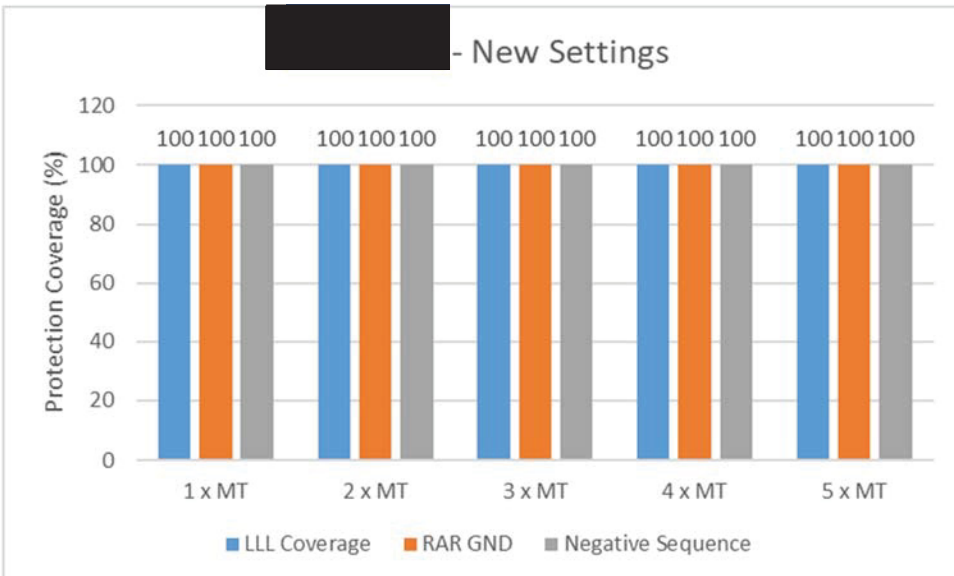


Figure F-19 – [redacted] Coverage

[redacted]

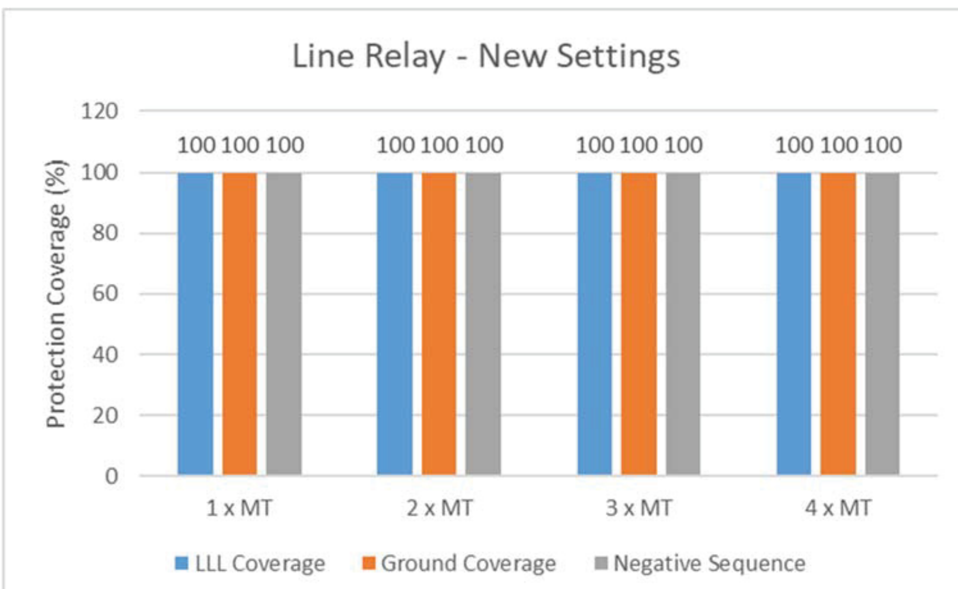


Figure F-20 – [redacted] Recommended Line Coverage

[redacted]

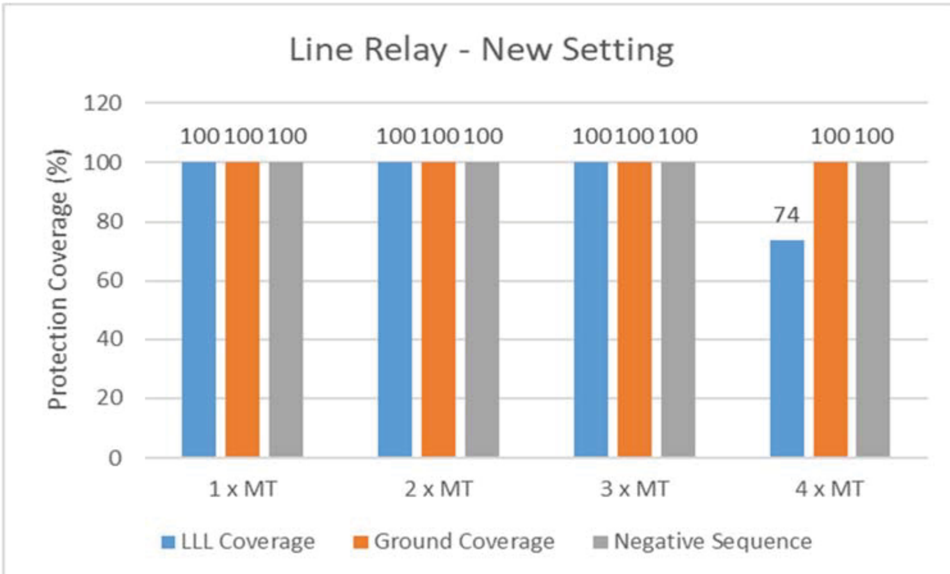


Figure F-21 – [redacted] Recommended Line Coverage

[redacted]

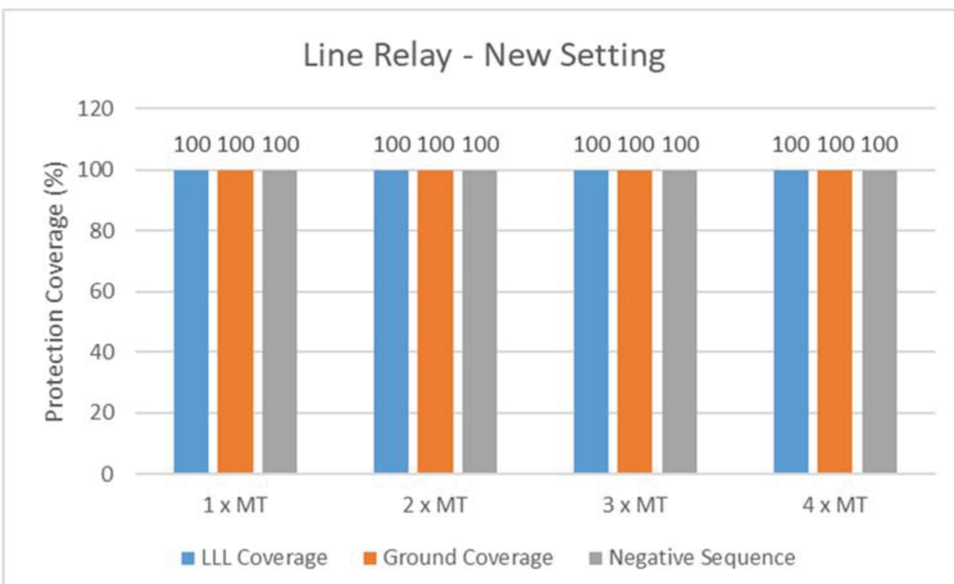


Figure F-22 – [redacted] Recommended Line Coverage

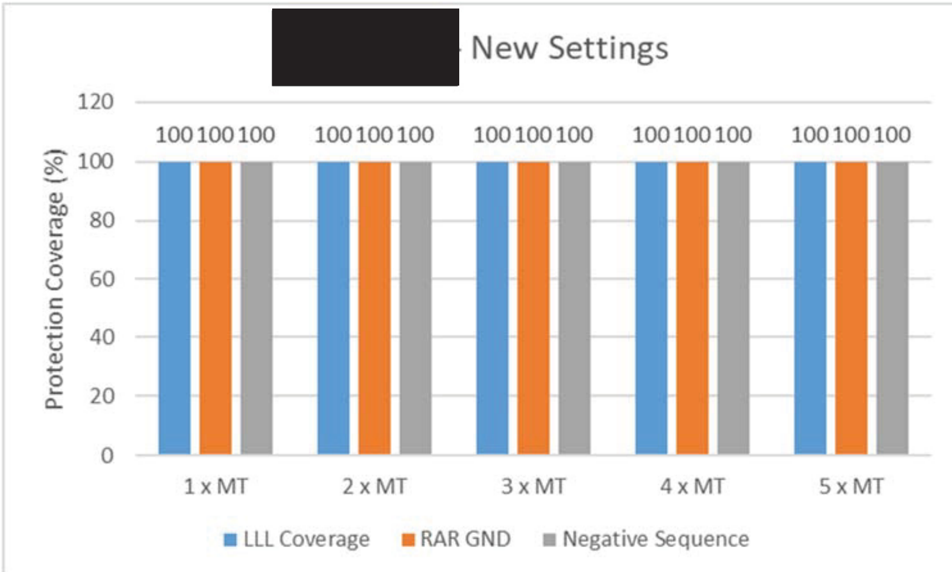


Figure F-23 – [redacted] Coverage

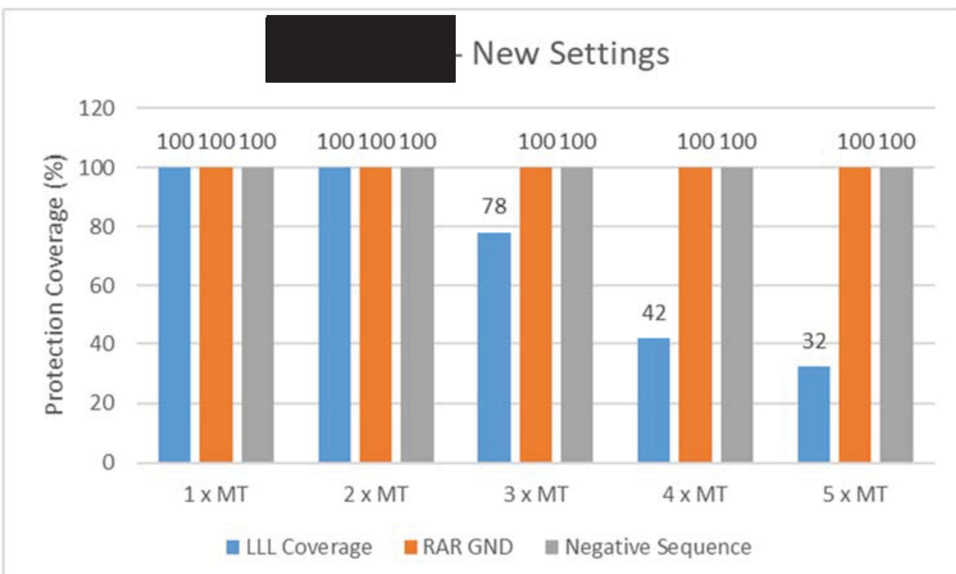


Figure F-24 – [redacted] Coverage

[redacted]

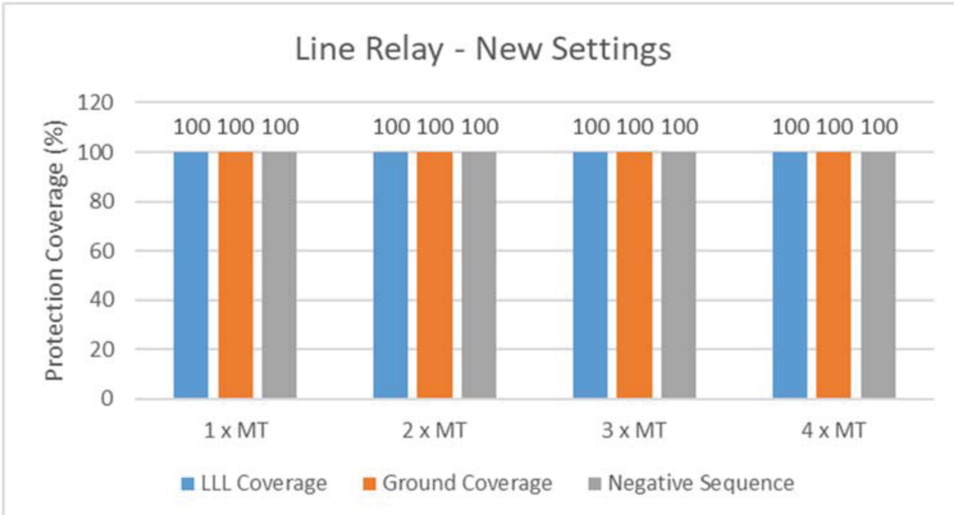


Figure F-25 – [redacted] Recommended Line Coverage

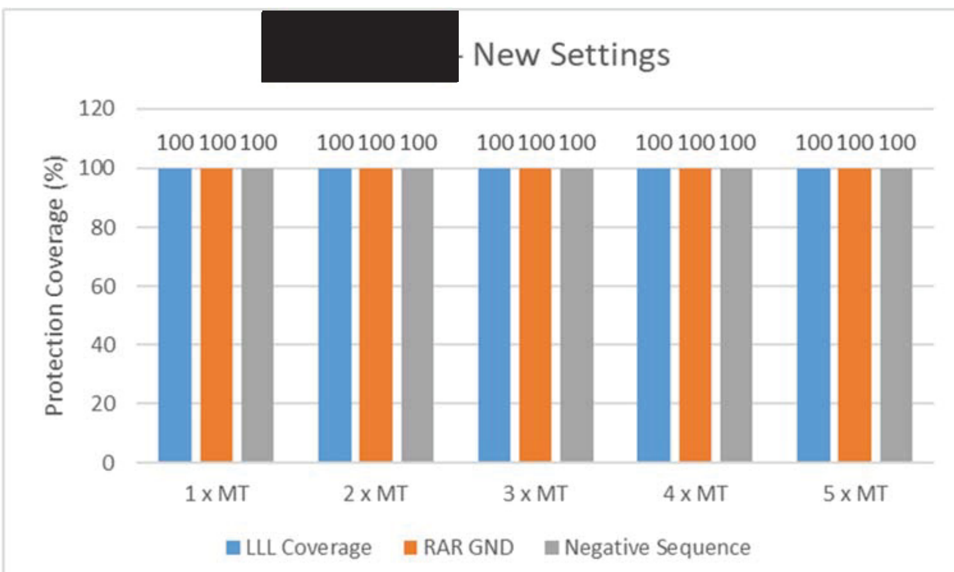


Figure F-26 – [redacted] Coverage

[redacted]

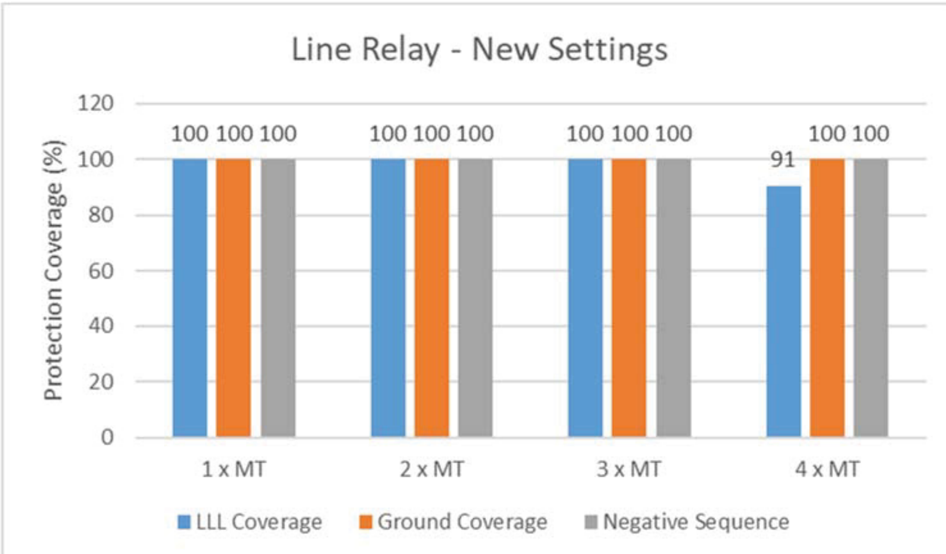


Figure F-27 – [redacted] Recommended Line Coverage

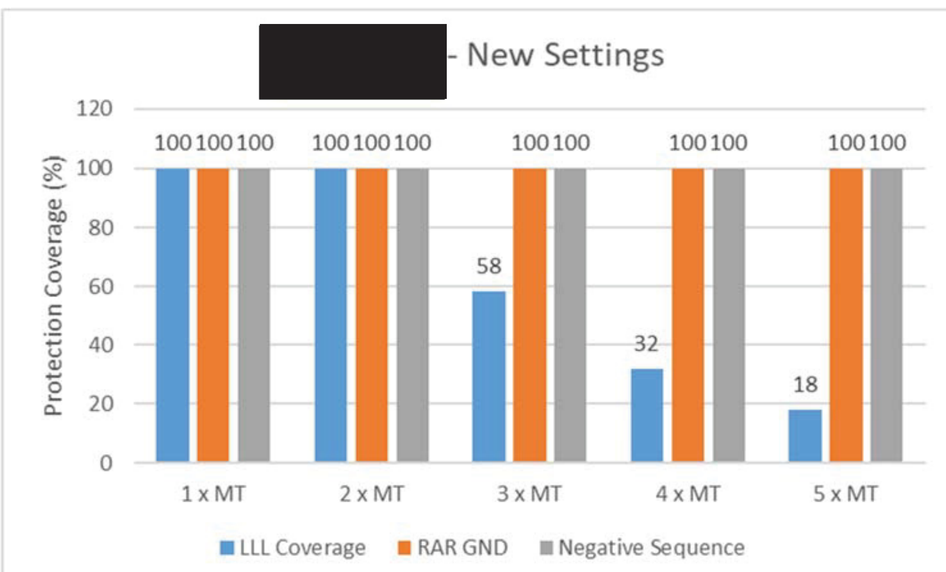


Figure F-28 – [redacted] Coverage

[redacted]

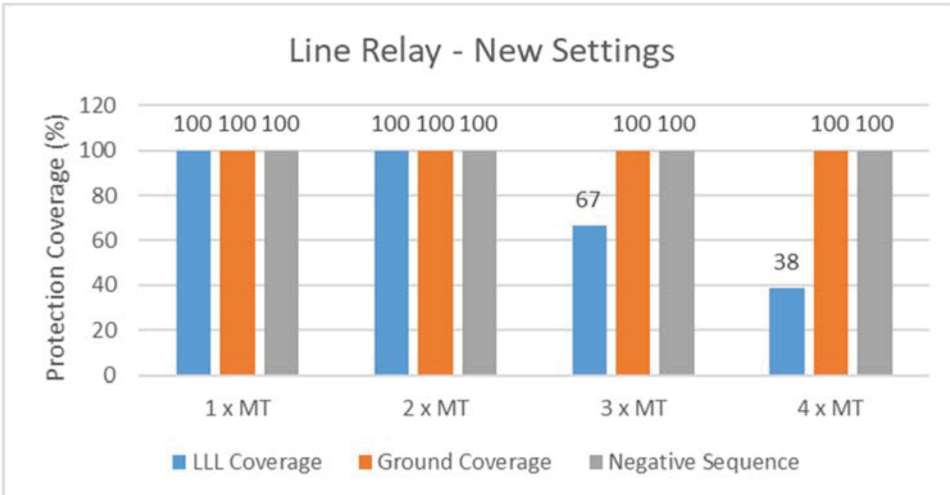


Figure F-29 – [redacted] Recommended Line Coverage

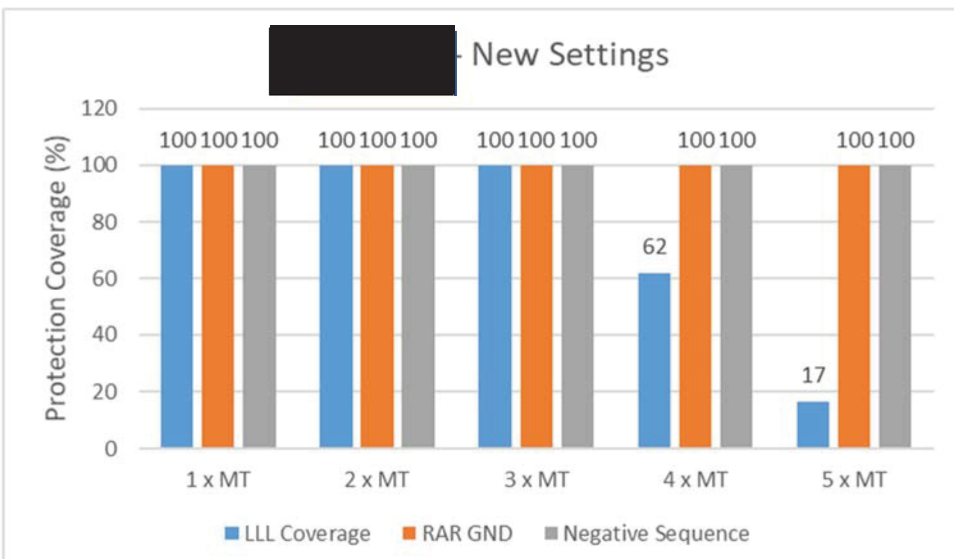


Figure F-30 – [redacted] Coverage

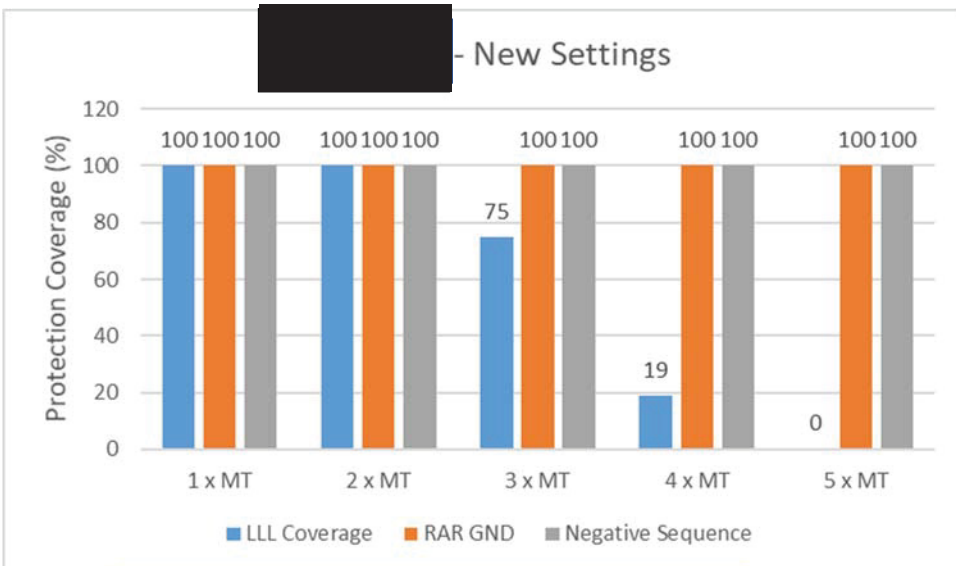


Figure F-31 [redacted] Coverage

[redacted]

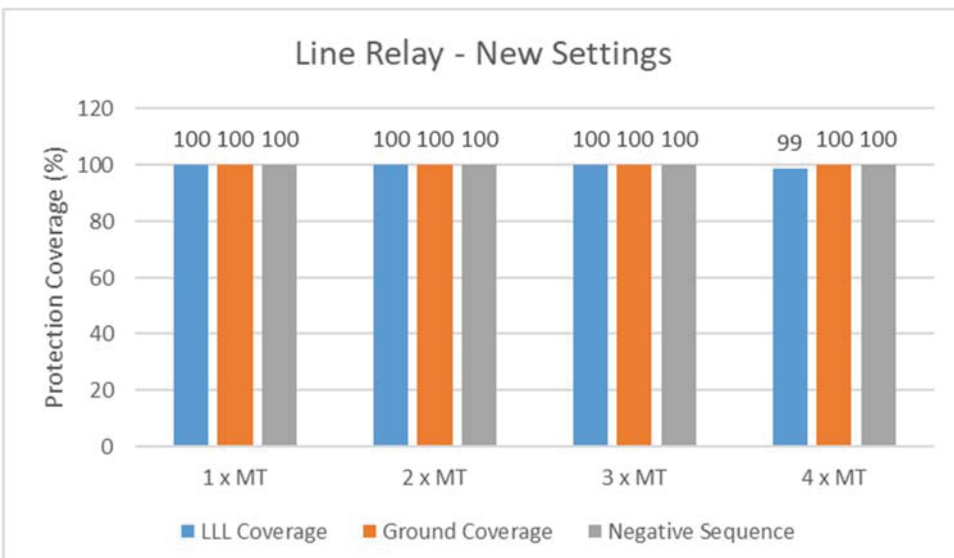


Figure F-32 – [redacted] Recommended Line Coverage

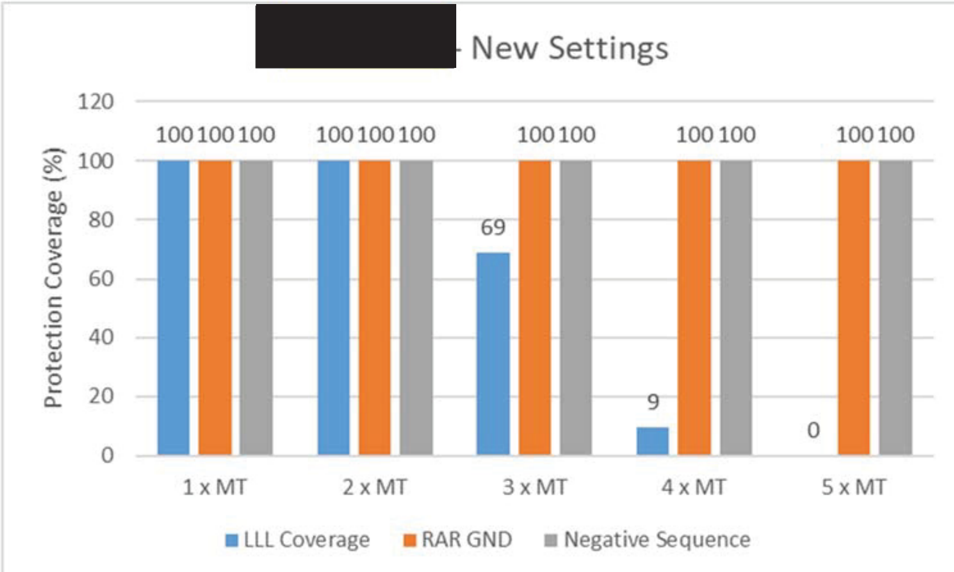


Figure F-33 – [redacted] Coverage

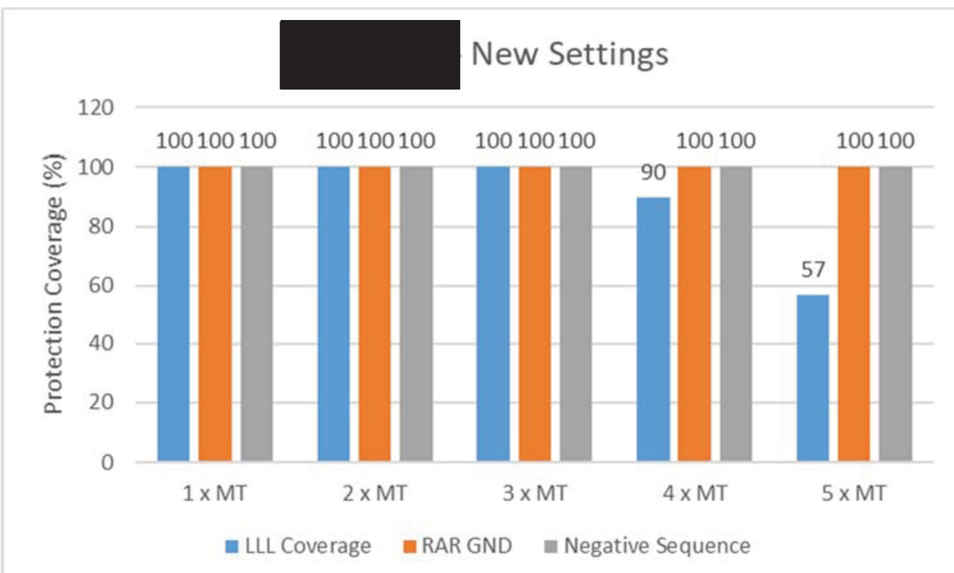


Figure F-34 – [redacted] Coverage

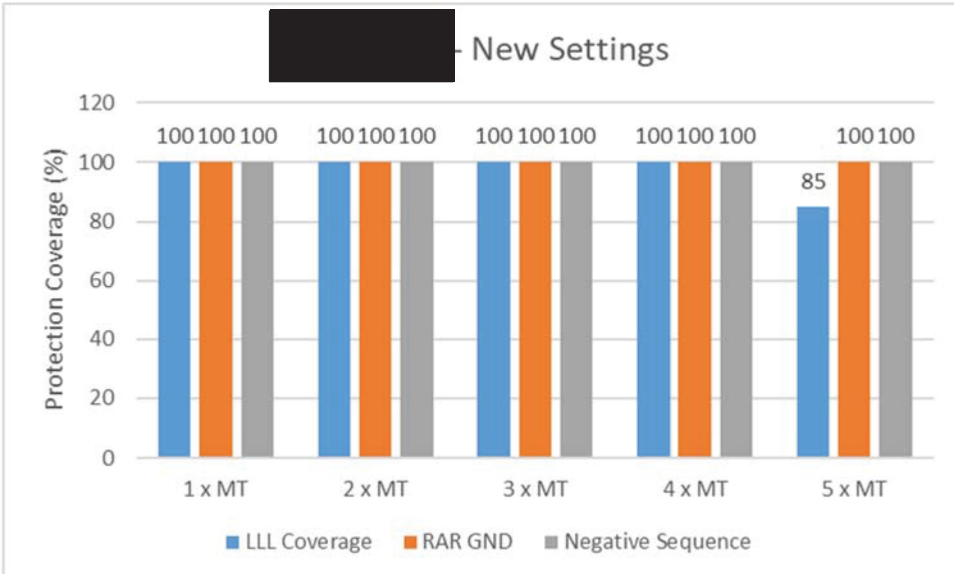


Figure F-35 – [redacted] Coverage

[redacted]

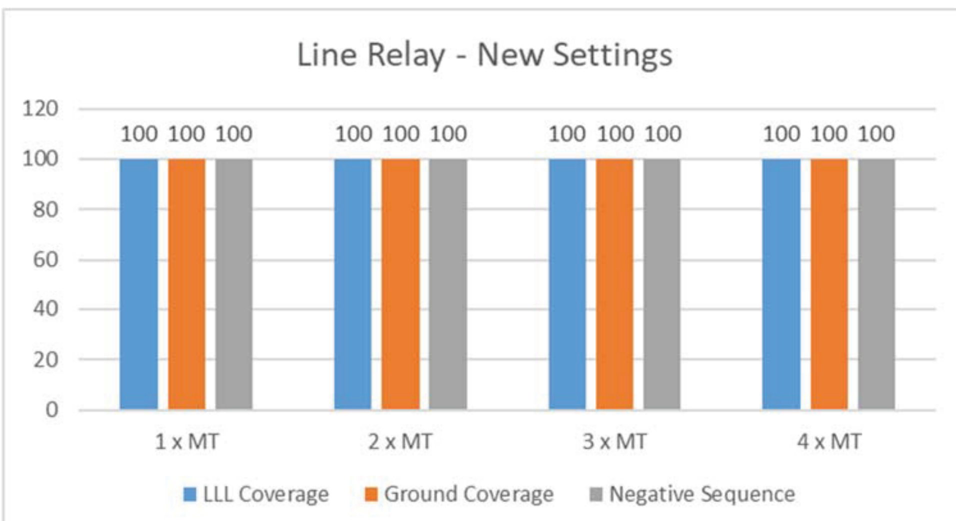


Figure F-36 – [redacted] Recommended Line Coverage

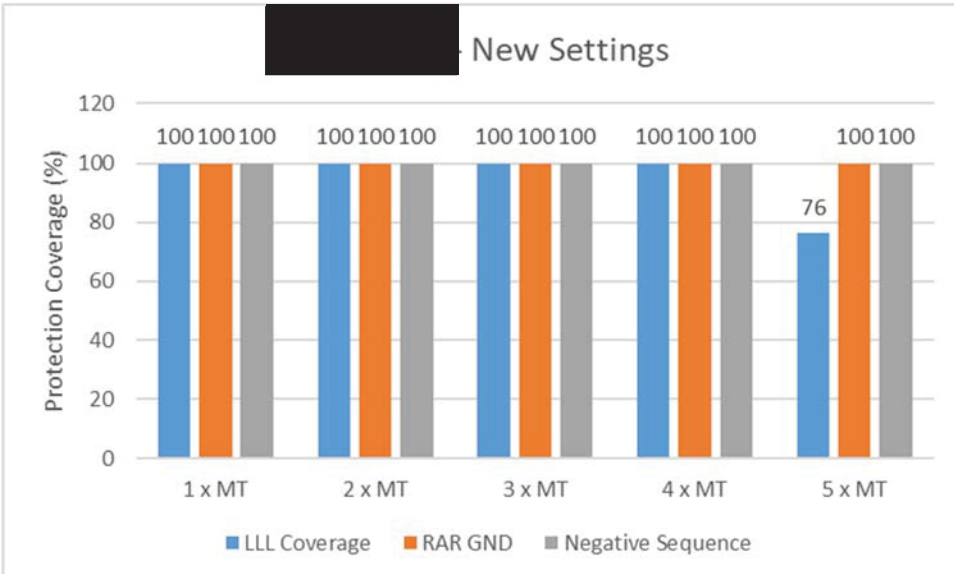


Figure F-37 – [redacted] Coverage

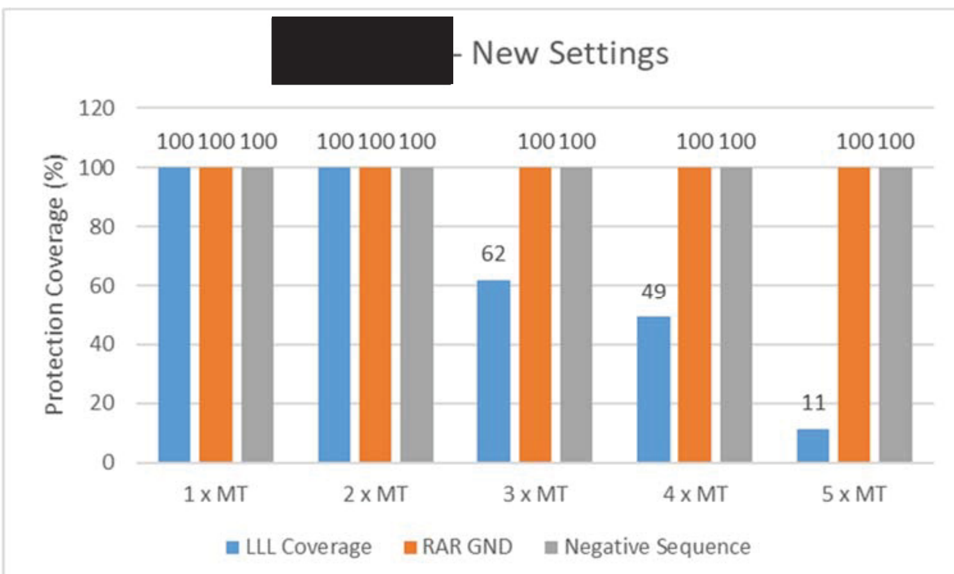


Figure F-38 [redacted] Coverage

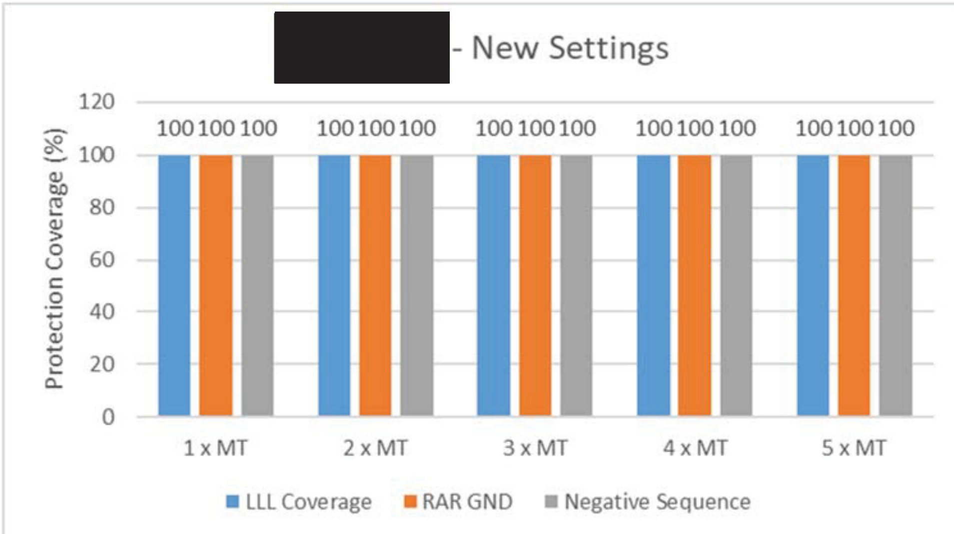


Figure F-39 – [redacted] Coverage

APPENDIX G – PEAK RELAY CURRENTS FOR FIDVR EVENTS

Table G-1 - Peak RMS Currents during 3ph and 1ph FIDVR Events for Varying Amounts of Single-Phase Compressor Loading

Circuit	Relay	Min Phase Trip (A)	Peak Line Current (A)						Peak Line Current (% of Min Trip)					
			3ph Disturbance			1ph Disturbance			3ph Disturbance			1ph Disturbance		
			20%	40%	60%	20%	40%	60%	20%	40%	60%	20%	40%	60%
[redacted]	[redacted]	300	434	572	679	406	554	670	145%	191%	226%	135%	185%	223%
[redacted]	[redacted]	240	107	147	179	96	135	172	45%	61%	75%	40%	56%	72%
[redacted]	[redacted]	280	326	424	499	311	424	496	116%	151%	178%	111%	151%	177%
[redacted]	[redacted]	220	267	346	406	257	347	404	122%	157%	185%	117%	158%	184%
[redacted]	[redacted]	720	991	1311	1594	983	1288	1515	138%	182%	221%	136%	179%	210%
[redacted]	[redacted]	400	554	685	774	534	648	712	139%	171%	194%	133%	162%	178%
[redacted]	[redacted]	100	132	186	237	136	190	236	132%	186%	237%	136%	190%	236%
[redacted]	[redacted]	100	109	155	195	112	157	193	109%	155%	195%	112%	157%	193%
[redacted]	[redacted]	720	1075	1532	1927	1108	1562	1926	149%	213%	268%	154%	217%	267%
[redacted]	[redacted]	50	49	58	70	33	42	50	97%	116%	140%	67%	84%	100%
[redacted]	[redacted]	720	1051	1500	1912	1068	1505	1861	146%	208%	266%	148%	209%	258%
[redacted]	[redacted]	100	25	37	47	14	19	23	25%	37%	47%	14%	19%	23%
[redacted]	[redacted]	720	1092	1579	2015	1118	1588	1972	152%	219%	280%	155%	221%	274%
[redacted]	[redacted]	720	1021	1362	1643	1002	1286	1483	142%	189%	228%	139%	179%	206%
[redacted]	[redacted]	340	173	218	246	158	201	229	51%	64%	72%	46%	59%	67%
[redacted]	[redacted]	140	172	217	244	156	200	227	123%	155%	175%	112%	143%	162%
[redacted]	[redacted]	70	44	54	62	46	61	67	62%	77%	88%	66%	87%	95%
[redacted]	[redacted]	70	75	95	110	81	108	118	107%	135%	157%	116%	154%	169%
[redacted]	[redacted]	720	1076	1481	1815	1079	1438	1701	149%	206%	252%	150%	200%	236%
[redacted]	[redacted]	360	532	710	861	490	639	753	148%	197%	239%	136%	177%	209%

Table G-1 - Peak RMS Currents during 3ph and 1ph FIDVR Events for Varying Amounts of Single-Phase Compressor Loading														
Circuit	Relay	Min Phase Trip (A)	Peak Line Current (A)						Peak Line Current (% of Min Trip)					
			3ph Disturbance			1ph Disturbance			3ph Disturbance			1ph Disturbance		
			20%	40%	60%	20%	40%	60%	20%	40%	60%	20%	40%	60%
[redacted]		200	184	246	293	149	188	220	92%	123%	147%	75%	94%	110%
		720	1008	1403	1760	1009	1384	1675	140%	195%	244%	140%	192%	233%
		720	1047	1482	1862	817	1023	1182	145%	206%	259%	113%	142%	164%
		275	484	598	690	473	617	700	176%	217%	251%	172%	224%	254%
		190	286	337	380	298	351	393	150%	177%	200%	157%	185%	207%
		720	952	1226	1480	947	1205	1392	132%	170%	205%	132%	167%	193%
		720	756	925	1056	699	845	934	105%	128%	147%	97%	117%	130%
		280	360	417	465	336	394	422	129%	149%	166%	120%	141%	151%
		80	105	132	152	103	125	137	132%	165%	190%	129%	157%	172%
		600	748	950	1121	736	928	1070	125%	158%	187%	123%	155%	178%
		120	102	112	125	96	106	118	85%	93%	104%	80%	88%	99%
		200	399	515	592	349	442	512	199%	257%	296%	174%	221%	256%
		170	287	375	444	297	379	436	169%	220%	261%	175%	223%	257%
		100	193	247	287	208	253	280	193%	247%	287%	208%	253%	280%
		720	1103	1609	2027	1112	1541	1875	153%	223%	282%	154%	214%	260%
		480	212	287	344	215	272	309	44%	60%	72%	45%	57%	64%
		150	100	136	162	101	128	144	66%	91%	108%	67%	85%	96%
		600	826	1066	1240	843	1056	1189	138%	178%	207%	141%	176%	198%
		480	13	18	23	13	18	23	3%	4%	5%	3%	4%	5%

Table G-2 - Peak Negative Sequence Currents during 3ph and 1ph FIDVR Events for Varying Amounts of Single-Phase Compressor Loading														
			Peak Line Current (A)						Peak Line Current (% of Min Trip)					
Circuit	Relay	Min Phase Trip (A)	3ph Disturbance			1ph Disturbance			3ph Disturbance			1ph Disturbance		
			20%	**40%**	**60%**	**20%**	**40%**	**60%**	**20%**	**40%**	**60%**	**20%**	**40%**	**60%**
[redacted]		300	77	110	132	91	141	189	26%	37%	44%	30%	47%	63%
		240	21	30	38	24	41	50	9%	13%	16%	10%	17%	21%
		280	57	79	94	68	112	138	20%	28%	34%	24%	40%	49%
		220	50	70	84	57	87	107	23%	32%	38%	26%	40%	49%
		720	187	281	353	222	380	502	26%	39%	49%	31%	53%	70%
		400	85	117	137	122	193	242	21%	29%	34%	30%	48%	61%
		100	24	39	50	36	64	88	24%	39%	50%	36%	64%	88%
		100	19	31	40	28	50	68	19%	31%	40%	28%	50%	68%
		720	209	330	426	257	467	631	29%	46%	59%	36%	65%	88%
		50	9	14	18	10	13	18	19%	28%	37%	20%	27%	36%
		720	209	334	435	245	450	611	29%	46%	60%	34%	62%	85%
		100	6	10	13	4	7	9	6%	10%	13%	4%	7%	9%
		720	209	336	438	264	481	656	29%	47%	61%	37%	67%	91%
		720	189	279	341	240	398	514	26%	39%	47%	33%	55%	71%
		340	32	45	54	31	52	67	9%	13%	16%	9%	15%	20%
		140	32	45	54	30	52	66	23%	32%	38%	22%	37%	47%
		70	6	8	10	9	15	19	9%	12%	15%	13%	22%	27%
		70	11	16	19	18	30	37	16%	22%	26%	25%	42%	53%
		720	197	304	387	267	454	600	27%	42%	54%	37%	63%	83%
		360	100	148	184	123	215	285	28%	41%	51%	34%	60%	79%
		200	32	48	59	29	50	68	16%	24%	30%	15%	25%	34%
		720	205	315	402	235	415	566	28%	44%	56%	33%	58%	79%

Table G-2 - Peak Negative Sequence Currents during 3ph and 1ph FIDVR Events for Varying Amounts of Single-Phase Compressor Loading															
			Peak Line Current (A)						Peak Line Current (% of Min Trip)						
Circuit	Relay	Min Phase Trip (A)	3ph Disturbance			1ph Disturbance			3ph Disturbance			1ph Disturbance			
			20%	40%	60%	20%	40%	60%	20%	40%	60%	20%	40%	60%	
[redacted]	[redacted]	720	199	314	406	162	255	323	28%	44%	56%	22%	35%	45%	
[redacted]	[redacted]	275	81	112	131	93	159	185	29%	41%	48%	34%	58%	67%	
[redacted]	[redacted]	190	52	69	78	60	81	88	27%	36%	41%	32%	42%	47%	
[redacted]	[redacted]	720	182	267	328	216	362	470	25%	37%	46%	30%	50%	65%	
[redacted]	[redacted]	720	126	173	204	151	246	311	17%	24%	28%	21%	34%	43%	
[redacted]	[redacted]	280	46	60	75	79	122	149	16%	21%	27%	28%	44%	53%	
[redacted]	[redacted]	80	21	30	37	29	43	53	26%	37%	47%	36%	54%	66%	
[redacted]	[redacted]	600	134	196	239	154	236	278	22%	33%	40%	26%	39%	46%	
[redacted]	[redacted]	120	23	26	31	40	44	55	19%	21%	26%	34%	37%	46%	
[redacted]	[redacted]	200	92	135	166	61	103	129	46%	67%	83%	31%	52%	65%	
[redacted]	[redacted]	170	93	134	161	110	158	187	55%	79%	95%	65%	93%	110%	
[redacted]	[redacted]	100	72	103	123	75	105	120	72%	103%	123%	75%	105%	120%	
[redacted]	[redacted]	720	186	296	384	289	501	676	26%	41%	53%	40%	70%	94%	
[redacted]	[redacted]	480	35	52	65	62	100	127	7%	11%	14%	13%	21%	27%	
[redacted]	[redacted]	150	22	29	35	32	51	63	15%	20%	23%	22%	34%	42%	
[redacted]	[redacted]	600	154	214	253	186	303	382	26%	36%	42%	31%	51%	64%	
[redacted]	[redacted]	480	2	4	5	3	5	7	1%	1%	1%	1%	1%	1%	

Table G-3 - Peak Zero Sequence Currents during 3ph and 1ph FIDVR Events for Varying Amounts of Single-Phase Compressor Loading														
Circuit	Relay	Min Gnd / Neut Trip (A)	Peak Line Current (A)						Peak Line Current (% of Min Trip)					
			3ph Disturbance			1ph Disturbance			3ph Disturbance			1ph Disturbance		
			20%	40%	60%	20%	40%	60%	20%	40%	60%	20%	40%	60%
[redacted]		30	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		10	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		20	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		12	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		180	37	68	95	191	325	422	20%	38%	53%	106%	180%	234%
		18	22	29	33	92	144	172	120%	163%	185%	511%	799%	957%
		10	6	10	16	33	60	81	57%	96%	159%	331%	597%	810%
		10	5	7	12	26	47	63	46%	74%	122%	259%	465%	626%
		180	46	77	123	253	473	655	25%	43%	68%	141%	263%	364%
		5	6	9	12	8	15	20	116%	183%	235%	160%	291%	402%
		180	41	75	118	242	449	617	23%	42%	65%	134%	249%	343%
		5.8	6	10	13	3	4	5	107%	173%	228%	54%	74%	94%
		180	42	69	111	257	474	655	23%	38%	62%	143%	264%	364%
		180	31	56	80	185	297	373	17%	31%	44%	103%	165%	207%
		10	10	14	17	10	15	19	98%	141%	169%	96%	153%	193%
		32 volts	10	14	17	9	15	19	n/a	n/a	n/a	n/a	n/a	n/a
		16 Volts	5	8	9	8	14	20	n/a	n/a	n/a	n/a	n/a	n/a
		32 Volts	4	6	7	17	31	45	n/a	n/a	n/a	n/a	n/a	n/a
		180	35	60	96	236	397	516	20%	33%	53%	131%	221%	287%
		9.2	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		5.8	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		180	38	74	112	233	415	550	21%	41%	62%	130%	230%	305%

Table G-3 - Peak Zero Sequence Currents during 3ph and 1ph FIDVR Events for Varying Amounts of Single-Phase Compressor Loading														
Circuit	Relay	Min Gnd / Neut Trip (A)	Peak Line Current (A)						Peak Line Current (% of Min Trip)					
			3ph Disturbance			1ph Disturbance			3ph Disturbance			1ph Disturbance		
			20%	40%	60%	20%	40%	60%	20%	40%	60%	20%	40%	60%
[redacted]		180	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		10	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		10	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		180	29	58	75	186	305	387	16%	32%	42%	103%	169%	215%
		180	28	50	58	113	181	221	16%	28%	32%	63%	101%	123%
		50	24	33	39	52	77	88	49%	66%	77%	103%	154%	176%
		6	18	26	31	20	29	34	299%	432%	514%	335%	484%	560%
		26	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		26	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		26	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		26	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		15	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
		180	40	63	78	255	444	586	22%	35%	43%	142%	246%	325%
		17.7	11	14	15	52	82	102	64%	81%	83%	296%	464%	576%
		17.7	15	21	24	29	43	52	82%	117%	138%	163%	243%	293%
		180	28	58	70	170	271	333	16%	32%	39%	95%	151%	185%
		120	1	1	1	3	5	7	0%	1%	1%	2%	4%	6%

[redacted]

Figure H-1 – [redacted] system during event.

[redacted]

Figure H-2 – [redacted]

[redacted]

Figure H-3 – [redacted] line

[redacted]

Figure H-4 – [redacted] line

[redacted]

Figure H-5 – [redacted] line

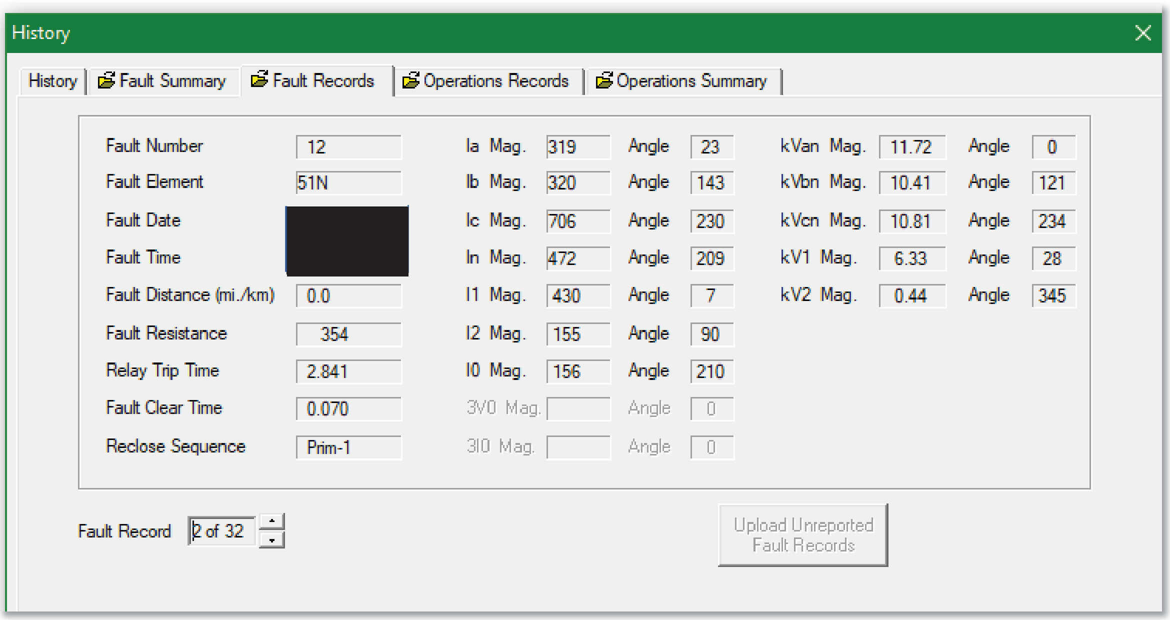


Figure H-6 – Fault records: [redacted]

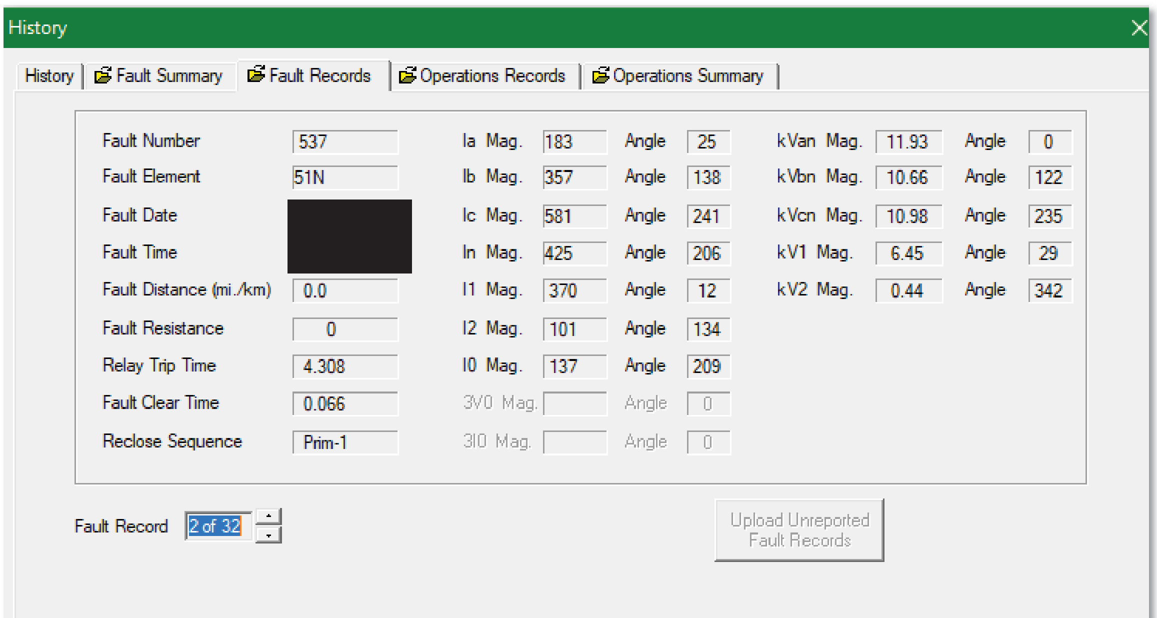


Figure H-7 – Fault records: [redacted]

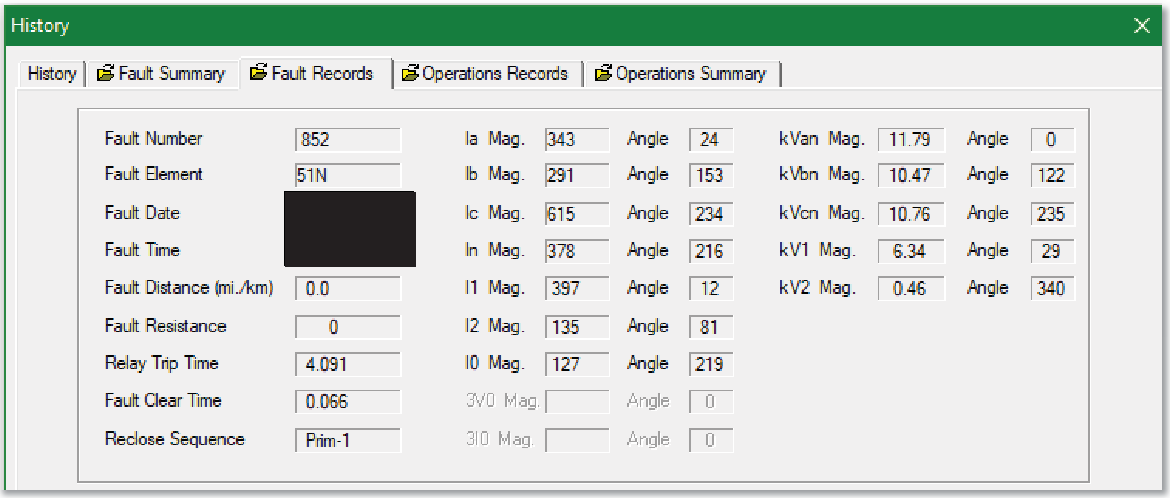


Figure H-8 – Fault records: [redacted]