Grid Strength Influence on Protection Settings: A Case Study Analysis and Solutions

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***Abstract*—Sympathetic tripping is a frequently encountered issue that disrupts the effective functioning of ground fault (GF) relays in distribution systems. This phenomenon tends to arise when operational feeders experience an unwarranted trip due to a fault occurring on a neighboring feeder. This study examines the causes and effects of sympathetic tripping involving overcurrent and GF relays in distribution networks. Detailed analysis uses recorded data from healthy feeders affected by reported sympathetic trip occurrences.**

***Index Terms*—External fault, internal fault, induction motor stalling, sympathetic trip, voltage dip, weak grid.**

I. Introduction

Sympathetic tripping generally refers to the tripping of a functioning object due to its protective devices, resulting from a high load current caused by a drop in voltage, which may arise from the "occurrence and clearing" of a fault in another component of the network [1].

The primary reason for sympathetic tripping is a voltage drop (sag) typically resulting from an external short circuit. This voltage drop affects the network, extending even to areas not directly involved in the short circuit current flow. Particularly in the distribution segment of the network, where this voltage drop is applied to a bus bar supplying heavy induction motor loads, it can lead to motor stalling [2], [3]. When the induction motors stall or are stalling, they can draw their full load current multiple times, causing the feeder that supplies this bus bar to carry a current that may significantly exceed its total load rating [2]. If this current surpasses the typical settings for short-circuit feeder protection, sympathetic tripping can occur. It becomes evident that in this scenario, the voltage drop is not detrimental to the feeder, nor does the relay function as backup protection for the motors.

In this scenario, the motor protection system will activate and disconnect the stalled motors after a certain delay, allowing enough opportunity to regain normal speed once the voltage is restored. This indicates that following the fault's resolution and the voltage restoration, the stalled currents from all impacted motors continue to flow through a single feeder for an extended period. Typically, these feeders are radial and are safeguarded by a basic phase and earth overcurrent relay, with a current setting just above the full load current and a time delay configured as briefly as possible to align appropriately with other relays upstream. Under these typical conditions, it is quite likely that the feeder protection will trip unintentionally, interrupting motor loads that could have regained speed, along with other non-motor loads connected to this feeder. [2], [3]

This unintentional tripping is not caused directly by an external short circuit activating overcurrent protection. Rather, the specific response of the load after the fault has been cleared and the voltage has been restored triggers the protection indirectly. [1]

In this paper, a local rural network in Saudi Arabia experienced sympathetic tripping upon faults on different feeders, so it is under extensive analysis. This analysis includes the transient mode as well as the steady state. It will be demonstrated later that during a voltage dip, while the external fault remains unresolved (on-event), the load current of the healthy object does not significantly increase. The excessive load current leading to sympathetic tripping would manifest only after the initial fault is cleared and the voltage is restored (post-event). The ferroresonance could introduce such behavior, so it has to be ruled out. Then, the existing relay protective settings are assessed thoroughly. Sets of recommendations are listed to tackle this problem.

The remainder of the paper is organized as follows. The sympathetic tripping is described in Section II, and some proposed solutions are listed in Section III. The case study setup is presented in SectionIV. Simulation of the case study scenarios is in SectionV. The discussion and analysis are in SectionVI. The conclusion and recommendations are in SectionVII.

II. Sympathetic Tripping

Distribution networks often experience various transient events that disrupt the effective functioning of the protection system, particularly the ground fault (GF) and overcurrent relays, thereby adversely influencing the reliability of the power system. There are two primary types of sympathetic tripping phenomena: unnecessary sympathetic tripping and engaged tripping phenomena. Unnecessary sympathetic tripping refers to the erroneous tripping of the unaffected feeder(s) during or following the clearance of a fault on an adjacent faulty feeder. This can occur in feeders with the same substation transformer or closed-loop feeders using the same feeding transformer. In contrast, engaged tripping is characterized by the appropriate required tripping of a feeder subjected to insulation stresses that arise sympathetically from a genuine asymmetrical fault occurring on an adjacent feeder that shares the same substation transformer bank. [4]

A fault on adjacent lines of the same voltage level or higher-voltage source lines commonly initiates delayed voltage recovery conditions (e.g., extended-duration voltage sags). The delayed voltage recovery problem results from the type of connected load. The culprit loads are large blocks of low-inertia induction motors that lose speed rapidly during a fault-caused voltage sag. Single-phase residential air conditioners are a typical application for these motors. Compounding their already easy-to-stall characteristics, these same motors must also work against the compressor's high refrigerant gas pressure. As these motors stall, they draw more current as the effective motor impedance decreases. Given that a single feeder could serve many air conditioners, the increase in feeder load current for the affected phase(s) can be appreciable. This large block of motor current draw leads to the troublesome sympathetic tripping by distribution feeder protective overcurrent relays. Delayed voltage recovery sympathetic tripping instances will likely increase as line loading and the number of single-phase, low-inertia air compressor motor loads increase. [1]

III. Sympathetic Tripping Solutions

In recent decades, the sympathetic trip phenomenon in distribution networks has attracted significant attention in power system protection research. Numerous initiatives have been undertaken to investigate the various causes of this phenomenon and mitigate false sympathetic trips.

A. Overcurrent and Ground-fault Relay Settings Adjustment

This is the simplest solution that entails no cost but has obvious drawbacks. That is the reduction in the protection sensitivity and the compromise to the chance of the overcurrent protective relays detecting some real faults. [4]

B. Reducing External Faults Clearing Time

This reduces the induction motor stall tendency, which, in turn, diminishes the post-event current. However, coordinating with other protection functions might introduce an intentional time delay, which is not preferable. [4]

C. Undervoltage Protection Function

Motor feeders are equipped with an undervoltage protection function to remove stalling motors. It is important to note that delayed undervoltage protection can cause a high current that needs a stall protection function to remove. Apart from the cost issue associated with this option, the incoming lines must be delayed to coordinate with the motor feeders. [4]

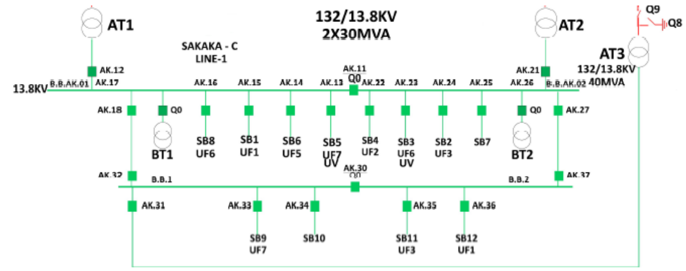

Fig. 1. Single line diagram of Network-B sub-station.

D. Block Logic on Overcurrent Relay

External faults cause undervoltage but do not necessarily impose high currents on local lines. This is the basis for the implemented logic, in which an overcurrent relay is temporarily blocked if the undervoltage relay is triggered. This ensures that the overcurrent relays are not operated sympathetically. [4]

E. Negative-Sequence Directional Current Logic

Should an external ground fault occur, a reverse negative-sequence current flows through the corresponding relay. Similarly, the zero-sequence current has a reverse flow for single-phase faults. These relays block the trip function temporarily till the external fault is cleared. [4]

F. Current-Limiting Techniques

Unlike previous relay-based techniques, this involves current-limiting devices, such as series reactors, network splitting, etc. The choked current reduces the voltage dips, which are the root cause of the motor stalling. [4]

IV. Case Study

A. Network-B Substation

Network-B 132/13.8kV sub-station has three numbers of 132/13.8 kV transformers (AT1, AT2 and AT3), 1x40 MVAr shunt capacitor at 132 kV bus and has the following interconnections at 132 kV bus:

- One circuit from Sakaka-A sub-station.
- One circuit from Sakaka-C sub-station.
- One circuit from Jouf-B sub-station.
- One circuit from Markazzallum sub-station.

Transformers AT1 and AT2 are 30 MVA each and run in parallel (the bus section is closed), feeding eight numbers of 13.8kV feeders. Transformer AT3 40 MVA runs independently and feeds four 13.8kV feeders (SB09, SB10, SB11, and SB12). The vector group of all transformers is YNyn0 (d11). The primary and secondary winding of the transformer's neutral point is solidly grounded.

The single-line diagram of the Network-B sub-station is shown in Figure 1.

B. Recorded Scenarios

The following problems are encountered in SB09, SB10, SB11 and SB12 feeders at Network-B:

- Incident 1: There was simultaneous tripping of the four feeders (SB09, SB10, SB11, and SB12). However, no information was found about the protection function being activated or the permanent faulty feeder, which may have initiated the simultaneous tripping.
- Incident 2: SB09 tripped due to a permanent fault, and at the same time, other feeders (SB10, SB11, and SB12) in the bus tripped with time-delayed overcurrent (IDMT).
- Incident 3: There was a permanent fault at SB10, and the feeder tripped with instantaneous POC and EF. At the same time, feeder SB11 tripped with a time-delayed OC.

he relay installed in these feeders is the static type (microprocessor-based without any communication). Asset Maintenance Department tested these feeder relays and found them working correctly except for the high relay operating time delay. The relay operating time delay was found to be 140 ms, and the total relay delay time + CB opening time = 200 ms.

The scope of the study was defined as follows:

- Root-cause analysis of the simultaneous tripping of the four feeders (SB09, SB10, SB11, and SB12).
- Recommendation of concrete and practical solutions pertaining to the problem encountered.
- Performing protection coordination studies and revision of settings of these feeders and their corresponding field Auto-close Reclosers (ACR).

These types of tripping are called “Sympathetic Tripping.” Spurious tripping of healthy feeders (sympathetic tripping) could be due to ferroresonance/resonance, voltage sag, poor voltage recovery, and behavior of motor load during a ground fault on one feeder, causing tripping in the healthy feeders. The studies are performed in EMT and RMS simulation software.

EMT software is used to discover the existence of ferroresonance/resonance and healthy phase voltage during a ground fault. RMS software is used to see voltage sag, recovery, and motor load behavior during a ground fault and clearing of fault clearing.

Disturbance recorder data is unavailable as 13.8kV feeder relays do not have the Transient Fault Recorder (TFR) connection. However, the faults at SB09 and SB10 are close to the 13.8kV Sakaka-B bus.

V. Simulations

EMT and RMS simulation software are used to determine the cause of spurious tripping of SB09, SB10, SB11, and SB12 relays. EMT simulation software analyzes ferroresonance/resonance and healthy phase voltage during a ground fault. RMS simulation software analyzes the behavior of motor loads (A/C load, pump, etc.) and voltage sag in the healthy feeder during and after fault clearing. In addition, a short-circuit study is performed.

A. System Modeling

A site visit, data collection, and single-line diagram review preceded the system modeling for RMS and EMT simulation purposes. Multi-site visits obtained feeder data, network short-circuit capacity, cable/overhead line data, transformer data, and feeder relay settings. The load modeling considered that it is an 80% motor load and 20% static load to assess the extent of motor stall impact.

The collected feeder data for both overhead line and underground cables involves: feeder length, feeder main stream length, transformer capacity, and peak load. Moreover, the lines’ positive sequence impedance and zero-sequence impedance are gathered to model the feeder main stream, overhead lines, and underground cables. The transformer data covers the capacity, voltage ratio, winding configuration, and impedance value. The overcurrent and ground fault relay settings of SB09, SB10, SB11, and SB12 feeders are collected for modeling. The other outgoing feeders, bus coupler, bus tie, and transformer relay settings were also collected.

These system data were used for the simulation to analyze spurious tripping of SB09, SB10, SB11, and SB12 feeders from Network-B. The system is modeled using RMS and EMT simulation software.

VI. Discussion and Analysis

A. EMT Simulation

1) Ferroresonance/resonance: Ferroresonance/resonance is a non-linear phenomenon occurring in a low-loss electric circuit containing a non-linear inductance (transformers), capacitor (cable/overhead line), and voltage sources. The existence of ferroresonance during and after a fault is examined. A ground fault near the Sakaka B 13.8kV bus is applied and cleared after 200 ms. Figure 2 gives each feeder’s voltage and current. This indicates no ferroresonance/resonance in the system; hence, the voltage and current behavior are standard during and after the fault.

Notice that the asymmetrical current takes nearly 1.5 cycles before the DC component decays, reaching the symmetrical fault current for the GF current at SB09-close-in case. The asymmetrical fault current is about 13.2 kA, and the symmetrical fault current is 10.5 kA, so the underlying network is not highly inductive (i.e., X/R is not significant). Another observation is that the grid is weak as indicated by the low available short-circuit currents and low X/R ratio, which stems from the fact that this network is in a rural area.

Furthermore, the steady-state RMS simulated GF RMS current listed in Table I for SB09-close-in case is 9.7 kA, the momentary short-circuit current (1/2 cycle). The equivalent peak short-circuit current is 13.7 kA, which is very close to the 13.2 kA peak current obtained from the EMT simulation. Similarly, the other steady-state cases can be compared to their transient EMT cases.

2) Healthy Phase-Voltage during a Ground Fault: For a ground fault in any of the feeders close to the 13.8kV Network-B bus, the healthy phase voltage is 1 pu (Refer

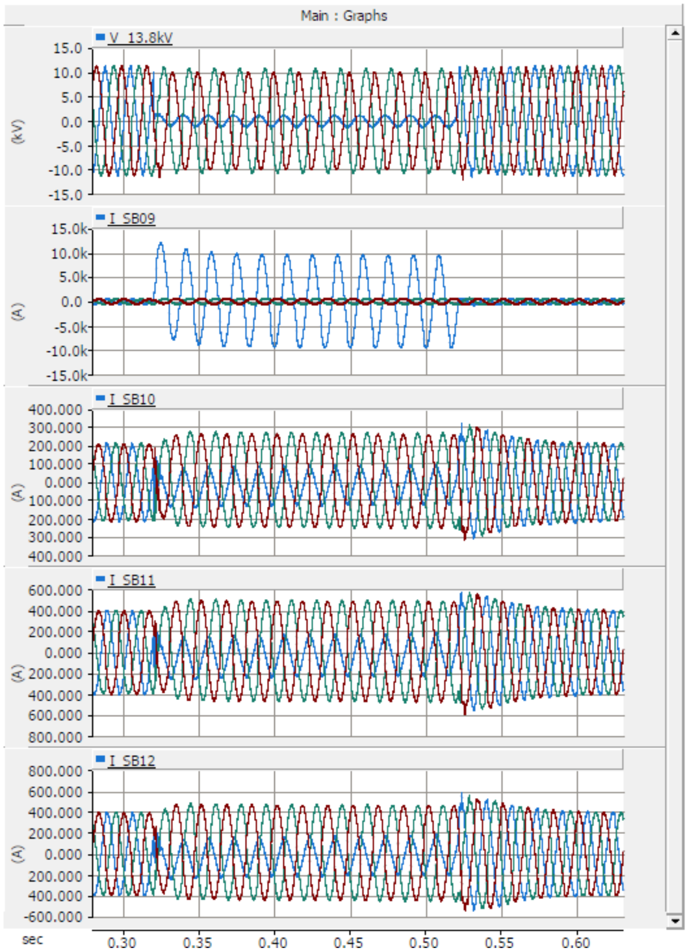

Fig. 2. EMT simulation for voltage and current for SB09, SB10, SB11 and SB12 feeders for a ground fault at SB09 close to the 13.8 kV Network-B bus.

TABLE I
FAULT CURRENTS

Location	**3-phase-ground kA**	**phase-ground kA**	**2-phase kA**	**2-phase -ground kA**
Sakaka 132kV	8.4	8	7.3	8.6
Sakaka 13.8kV	9	10	7.8	10
SB09–Close-in	8.4	9.7	7.2	9.5
SB09–Remote end	2.6	1.7	2.3	2.4
SB10–Close-in	8.6	9.4	7.5	9.1
SB10–Remote end	3.5	2.9	3	3.3
SB11–Close-in	8.6	9.3	7.4	9.1
SB11–Remote end	1.8	1.1	1.6	1.7
SB12–Close-in	8	9.2	6.9	9.2
SB12–Remote end	2.6	1.7	2.2	2.4

Figure VI-A2). No voltage rise is observed in the healthy phase since the 13.8kV system is solidly grounded. At the same time, for a ground fault at the remote end of any of the feeders, the maximum healthy phase voltage is 1.3 pu (Refer Figure VI-A2). This temporary overvoltage is acceptable, and it would not cause any mal-operation/spurious tripping of relays.

B. *RMS Simulations*

A short circuit study is performed, and the fault currents for the Network-B 132kV bus, Network-B 13.8kV bus, close to 13.8kV outgoing feeders, and remote end of the feeders are provided in Table I.

1) Sympathetic Tripping due to Voltage Sag: A ground fault in the system will cause voltage sag or dip with different magnitudes and durations, followed by voltage recovery to normal. This 'Voltage Sag' (voltage does not recover after fault clearing) causes the tripping of other system feeders, termed "Sympathetic Tripping Phenomena."

The sympathetic tripping phenomenon is essentially a transient pickup of relays of other healthy feeders due to the conditions created by a fault on another system feeder.

Sympathetic tripping at the distribution network is due to voltage recovery problems on the low-voltage side of the system. Any phase-to-earth fault on one phase will dip the voltage, and with the resulting imbalance, the single-phase A/C motors (hang-on) stall, causing heavy currents. The voltage reduction and the impedance of A/C motors cause heavy currents until they get disconnected under voltage protection. Thus, they cause a delay in voltage recovery after the fault is cleared. Also, voltage imbalance following a fault in any of the phases causes undesired relay pickup due to current surges in the earthed neutrals and lines. The distribution feeders that are most affected have voltage drops and are overloaded post-to faults.

The SB09, SB10, SB11, and SB12 feeders are modeled with the system parameter described in section 6. Maximum load current of 299 A, 251 A, 260 A and 280 A is considered for SB09, SB10, SB11 and SB12 feeders, respectively. The loads are considered as 80% of motor load and 20% static load.

The study cases and results are summarized in Table II.

Table II indicates that motors are stalled for cases 3, 4, and 6. These cases are simulated with 50% of the load (i.e., 146 A, 122 A, 125 A, and 135 A for SB09, SB10, SB11, and SB12 feeders, respectively) to show that motors are stalled for 50% of the feeder load.

The maximum fault clearing time for each feeder to avoid A/C motor stalling and duration of high current (above relay pickup current of 360 A) are calculated. The results are given in Table III. Most motors are stalled over the maximum fault-clearing time and do not recover from high currents even after the source voltage returns to normal.

2) Relay Setting Review: The existing relay setting is carefully reviewed. The protection coordination curves are given in Figure VII and Figure VII for the proposed phase and earth overcurrent relay setting, respectively. The instantaneous

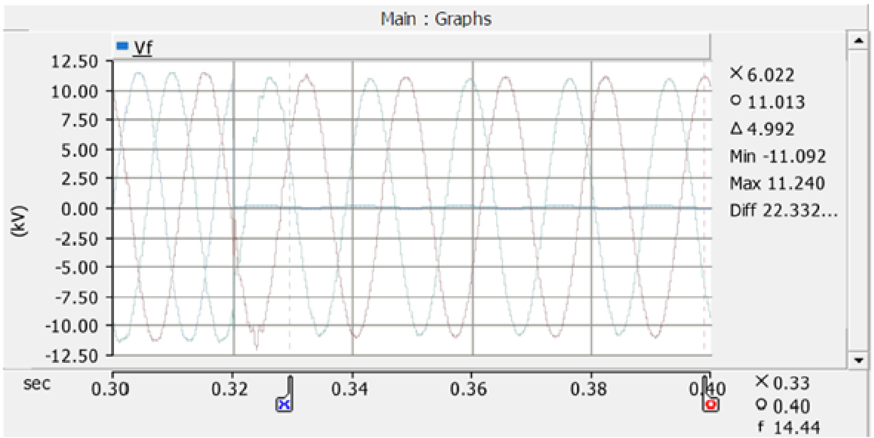

Fig. 3. Voltage at fault location for a ground fault at any one of the outgoing 13.8kV feeders close to the 13.8kV Network-B.

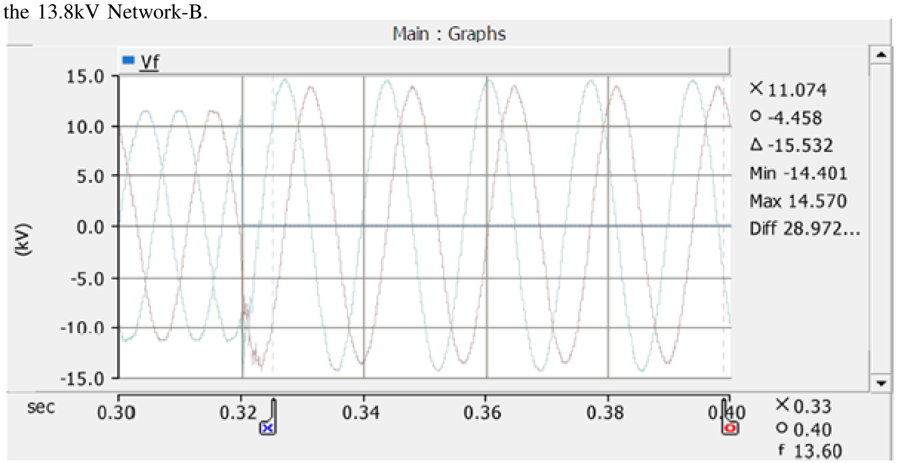

Fig. 4. Voltage at fault location for a ground fault at remote end of any outgoing 13.8kV feeder.

TABLE II
RESULTS OF SYMPATHETIC TRIPPING DUE TO VOLTAGE SAG

Case	Fault	Fault location	Fault clearing time	Voltage (during fault)	Voltage (after fault)	Max. feeder current post fault	Remarks
1	1-phase-ground	SB09–Close-in	70ms	59.5%	102.5%	276 A	Motors are not stalled
2	1-phase-ground	SB09–Close-in	100ms	57.5%	102.5%	276 A	Motors are not stalled
3	1-phase-ground	SB09–Close-in	300ms	53.5%	90.5%	804 A	Motors are stalled
4	3-phase-ground	SB09–Close-in	70ms	8%	90.5%	804 A	Motors are stalled
5	1-phase-ground	SB09–Remote	500ms	93%	105%	278 A	Motors are not stalled
6	3-phase-ground	SB09–Remote	500ms	61.5%	90.5%	804 A	Motors are stalled

TABLE III
MAXIMUM FAULT CLEARING TIME

Case	Fault	Fault location	Feeder	Max fault-clearing time to avoid motor stalling	Duration of high current for the maximum fault clearing time
1	1-phase to ground	SB09–Close-in	SB10 feeder	141 ms	441 ms
			SB11 feeder	141 ms	451 ms
			SB12 feeder	128 ms	738 ms
2	3-phase to ground fault	SB09–Close-in	SB10 feeder	¡ 30 ms	motors will stall even for 30 ms fault clearing time
			SB11 feeder		
			SB12 feeder		
3	1-phase to ground fault	SB09–Remote end	-	¿ 2s	motors will not stall even for 2 seconds fault clearing time
4	3-phase to ground fault	SB09–Remote end	SB10 feeder	265 ms	435 ms
			SB11 feeder	268 ms	458 ms
			SB12 feeder	243 ms	963 ms

setting of the SB09 feeder covers 90% of ACR distance. The changes in the relay settings ensure that the slow voltage recovery is averted. For instance, the phase overcurrent new setting for the SB09 feeder had to compromise between the curve type and the TMS setting. It is preferred to have the very inverse curve type to avoid the voltage recovery issue, but the TMS shall be extended so as not to lose coordination with the SB10 feeder setting.

Alternatively, voltage-restrained overcurrent (51V) adjusts the pickup value per the voltage tap to account for the current's varying level. Subsequently, the faulty motor feeder is isolated fast enough to avoid the motor stall of other healthy feeders. This is evident in case 2 and case 3 in Table III, where the voltage levels for both cases are almost the same, but the fault-clearing times are significantly different. The 51V would provide an alternative solution for such a problem if the relay setting adjustment introduces complications in the coordination process.

VII. Conclusions

The root cause analysis concluded that the voltage sag during a fault in one feeder close to the 13.8kV Network-B bus caused the tripping of other feeders. The tripping incidents also show that the fault is close to the 13.8kV Network-B bus.

Based on the analysis, the following are observed:

- For a ground fault, the fault should be cleared within 100 ms to avoid the A/C motor stalling. For a phase fault, the motor goes into a stall due to a very low voltage dip during the fault.
- When the motors are not stalled, they take approximately 1 s to recover to nominal voltage and current.
- When the motors are stalled, they do not recover from high current even after the nominal source voltage.
- Reducing the feeder load to 50% is also not helping to avoid motor stalling.

Based on the observations, the following are recommended:

- Replace the existing relays with numerical relays to have less operating time. Decreasing the fault clearing time will reduce the actual time that the motor load is subjected to reduced voltage, thus avoiding the stall tendency of motors. The operating time of existing relays at 13.8 kV feeders (MCGG) is approximately 200 ms.
- Using Very Inverse (VI) time overcurrent characteristic for phase relays will lead to a longer time for the relay to operate at healthy feeders. Hence, the voltage may recover and avoid the stall tendency of motors.
- Considering the above points. The maximum fault clearing time for a remote end phase fault is 760 ms.
- Under-voltage tripping addressing the motor stall scenario to trip the feeder is necessary.
- Keeping bus-tie breakers normally open so ground faults impact fewer feeder lines.
- Utilizing 51V protection function as an alternative to the relay setting resolution or in conjunction.

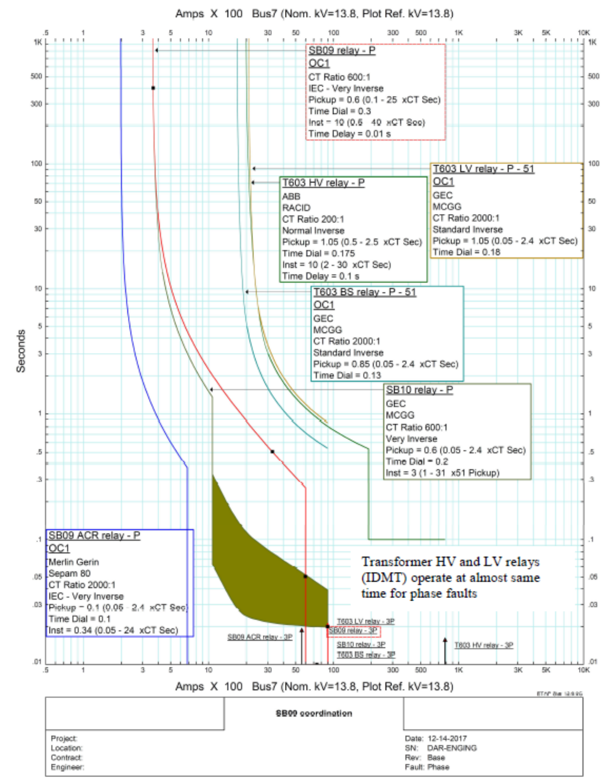

Fig. 5. Phase overcurrent coordination curve.

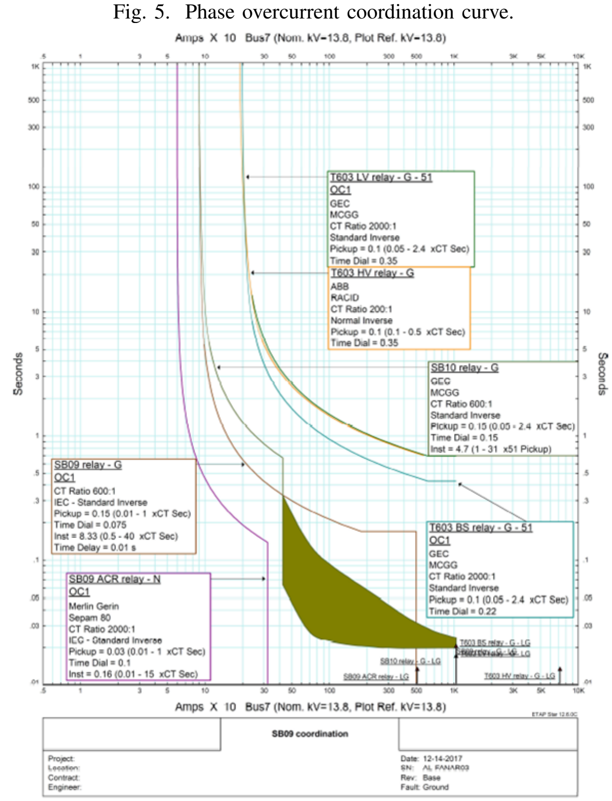

Fig. 6. Earth overcurrent coordination curve.

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VIII. Vita

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