Protection Challenges of a Resistance Grounded Distribution Feeder with Fused Taps

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Abstract— **This paper focuses on a multi-phase fault that occurred in a 13.8/0.48kV transformer. This transformer was one of many fused taps on this 13.8kV feeder. The nature of this fault resulted in the fuses interrupting current on only one single phase. The resulting fault was a resistance-limited ground fault which was ultimately cleared by the 51G function, removing multiple transformers from service.**

Analysis of the COMTRADE file and other troubleshooting data gives insight into the evolving nature of some transformer faults and serves as a catalyst for discussion of the merit of sensitive transformer differential pickup settings. Other topics that arise from the observations of this event include the sometimes-overlooked consequence of limiting ground fault current through resistance grounding, the effectiveness of transformer dissolved gas analysis in determining the nature of a transformer fault and the usage of communications to expedite fault clearing.

***Index Terms*—Fused Taps, Protective Device Coordination, Differential Protection, Transformer Faults**

I. INTRODUCTION

The lessons and observations of this paper are linked to a multi-phase fault that occurred in a transformer, which was one of many transformers fed by a fused tap off a single 13.8kV distribution feeder breaker. For reference, a one-line is provided in Appendix A. The details of this fault are well known because the distribution feeder's relay captured a transient record when it detected the fault and cleared the fault by tripping the breaker. Details found in the relay's COMTRADE file are provided in Appendix B.

The distribution topology shown in Appendix A, a distribution feeder with fused taps is ubiquitous in utilities. Utilities are commonly overhead construction with a solidly grounded neutral. The higher ground fault current available in a solidly grounded neutral system is imperative to detecting and clearing single phase-to-ground faults, including downed conductors. Also, the solid ground provides superior voltage stability. As neutral impedance increases, so does the line-to-ground potential in the unfaulted phases. These are safety considerations.

Operationally, fuses provide several advantages. Fuses are possibly the oldest, most intuitive and cost-effective of electrical protection devices. They are capable of interrupting high levels of fault current without requiring any other extra apparatus like breakers, relays, DC battery systems, etc. Fused taps are relatively inexpensive and simple to add to a distribution feeder.

A significant difference between the architecture of the ubiquitous distribution feeder with fused taps and the system in Appendix A is the grounding method. Appendix A shows a low-resistance grounded system. Both the utility and generator are resistance grounded with 300 amp (26.5 Ohms) resistors. This limitation on ground fault current significantly contributed to the miscoordination that ultimately resulted in a large loss of plant load.

II. FAULT ANALYSIS

The waveform in Appendix B clearly shows a phase-to-phase fault between phases A and C with a peak magnitude of approximately 4,000 amps. The duration of this fault is less than two cycles because the C-phase 100E fuse interrupts the phase-to-phase fault current very quickly. Because the A and C fuses did not interrupt the current at the same time, phase A fault current continued to flow through the ground as a resistance-limited ground fault. Seventeen cycles later, the feeder protection IED's time-delayed ground overcurrent element tripped and triggered the COMTRADE capture.

This fault analysis has been confirmed because a melted fuse link was found in the C-phase of the fused switch feeding the transformer. Post-fault analysis also determined that the transformer had water inside the tank, a turn-to-turn fault, and elevated levels of acetylene and ethylene in the oil sample. Clearly, this transformer had problems and needed to be isolated from the rest of the circuit.

III. SOLUTION ALTERNATIVES

A. Address the Mis-Coordination with Extra Time Delay

The 51G relay at the upstream feeder breaker tripped sooner than the fuses that protected the faulty transformer, a classic miscoordination. Increasing the delay characteristics of this 51G is possibly the simplest solution to preventing another widespread plant outage, but it has consequences. Extra time delay means extra damage to the faulted equipment on the circuit. Extra delay at the feeder also requires extra delay at the source transformer and generator, meaning those pieces of equipment would experience more duress during faults.

The 100E fuse curve in Appendix C has a 90 ms total clear time at 800 amps, 600 ms at 400 amps and 8,000 ms at 300 amps. It is extremely inverse. Restricting the ground fault magnitude with a resistor that is too large might mean that time-coordination is not possible without exceeding the I^2t rating of the resistor. The time-delay characteristic should be compared to the resistor's rating, which is commonly 10 seconds at its current rating per IEEE Std. 32[1].

B. Remove the Resistors, Solidly Ground the System

If the grounding resistor is removed, the available short circuit current increases by multiple orders of magnitude. When faults occur on equipment fed from the fused taps, the current magnitude would likely be enough to instantaneously blow the fuse link in all phases involved in the fault. Although this solution easily solves the challenge of protective device coordination, it means that any ground fault on the system would subject equipment to thousands of amps instead of hundreds. This solution trades longer clearing times and low levels of current for quicker clearing times and high levels of fault current.

In the architecture of Appendix A, a solidly grounded system exposes the source transformer and the generator to potentially catastrophic damage for a fault that could otherwise be limited to a few hundred amps.

C. Use Relays with Communications to Expedite 50/51G Clearing Times.

If breakers are cost-prohibitive, protective relays can still offer some value. Equipping each fused tap with a zero-sequence CT and an IEC61850 GOOSE-capable IED, it is possible to create a scheme that enables the feeder breaker's ground overcurrent relay to use a fuse-coordinated delay when the fault is detected on a fused tap but a faster time delay otherwise. This is effectively a zone-selective interlocking scheme that specifically addresses long clearing times because of coordination with fuses. It solves the problem of mis-coordination but still allows fast clearing for some faults. It does not improve protection for any equipment fed from those taps.

To implement a 50G zone selective scheme, the fused tap architecture must be physically capable of accommodating a zero-sequence CT. Installing bare conductors on an overhead tap through a zero-sequence CT is not practical, but it is common practice in insulated, metal-enclosed distribution equipment.

D. Use Relays and a Fast Grounding Switch

Another concept that makes use of protective relays without an immediate breaker (or fault-interrupting recloser) is to use the 50G relay to actuate a fast-acting grounding switch. The purpose of this grounding switch is to force a bolted three-phase-to-ground fault, which would instantly blow all three fuses, ensuring that the fault is isolated without de-energizing all other load on the system.

Forcing a three-phase fault onto the system is normally an occurrence to be avoided at all costs because of the electrical and mechanical stress induced by the extremely high short circuit current magnitudes. This scheme relies on the current limiting and fast-tripping nature of the fuses to minimize those stresses.

In making the decision to use a fast grounding switch versus allowing the ground current to persist until the slower ground overcurrent operates, it can be helpful to evaluate the resulting I^2t stresses. The resulting I^2t for a 400 amp fault that lasts 10 seconds before being interrupted is roughly equal to the I^2t for 14 kA that is interrupted after 8 ms[2].

Installing a fast earthing switch adds cost to the system, but there is an added benefit of arc flash reduction. Transformers fed by fused taps commonly result in extremely high incident energy because of the slow fuse clearing time. In addition to being actuated by a relay to clear transformer faults, it can also be actuated by a relay or arc-flash sensor to marginalize arcing faults that are particularly worrisome at the incoming breaker of the equipment supplied by the transformer.

E. Use Breakers Not Fuses

If breakers had been used, a protective relay could have detected the phase-to-phase fault and tripped all three poles. Differential protection or instantaneous 50G relays could have avoided the prolonged clearing time of the upstream time-delayed ground overcurrent relay. Of course, the installation of breakers, relays, instrument transformers, and a reliable energy storage system make this the most expensive of any conventional solution.

F. Install a Proactive Transformer Monitor

Because the root cause of this event was moisture leaking into the transformer coil from the bushings, there is a possibility that an online oil/dissolved gas analyzer (DGA) device could have raised an alarm prior to causing the phase-to-phase fault. The success of this solution is predicated on the notion that the water leak occurs gradually and that the alarm is actively monitored so that the transformer can be taken out of service prior to failure[3].

IV. LESSONS PERTAINING TO APPLICATION OF TRANSFORMER DIFFERENTIAL

Selecting a differential pickup is an exercise that must balance the need for sensitivity versus the need for security. Typically, a less sensitive pickup is considered more secure and thus less likely to result in a nuisance trip and increase overall reliability. The details of this transformer fault provide an opportunity to challenge that conventional wisdom.

Assuming the faulty transformer had been protected by a circuit breaker with transformer differential relaying instead of a fused tap, a higher, more conservative 87 pickup would have likely detected the transformer phase-to-phase fault. Notice that the initial phase-to-phase current is slightly less than 2kA.

Possibly the least sensitive, conservative methodology of choosing a transformer differential pickup is to select a pickup that is twice the transformer maximum rated load. Application of this method implies that the process load being served by the transformer is more important than detecting incipient faults within the transformer windings. This high pickup would allow an operator to inadvertently short all the CT's on one winding without triggering the 87 pickup, even under maximum loading conditions. Maximum loading conditions of a 2000 kVA ONAN transformer at 13.8kV is 94 amps, 12% higher than its base rating. Using the extremely conservative method would yield an 87 pickup of 200 amps.

In the context of this fault, an 87 pickup of 200 amps would have resulted in a successful trip and isolation of this fault that occurred in the primary windings. However, the fact that there were only 2,000 amps of fault current for a fault in the primary windings casts doubt that there would be sufficient fault current if the fault had occurred in the secondary windings.

The calculated three-phase bolted fault current at the primary bushings of the transformer was in excess of 10kA. This implies that the impedance in the fault current, including that of the primary windings and in the water was enough to reduce the fault current by 80%. It stands to reason that a similar fault occurring on the secondary windings would not have had sufficient fault current to operate the 87 with an extremely conservatively set pickup. The result of the conservatively set 87 pickup would have resulted in a much longer clearing time, prolonged voltage drop on the distribution circuit, and unless the backup time-overcurrent protection was properly coordinated, a similar outage that the 87 protection was supposed to prevent.

V. CONCLUSIONS

Transformer loads are commonly added to a distribution circuit by adding a fused tap because it is a relatively simple, inexpensive, effective method. The COMTRADE record of the fault that serves as the focus of this paper shows that fuses, while largely effective for high short circuit current, has deficiencies when tasked with clearing resistance-limited ground faults. Low levels of ground fault current, either due to resistor size, extra fault resistance or an operating scenario that removes a ground source, can yield extremely long fuse clearing times.

There are various solutions to the problems posed by a fused tap, each with its own challenges. Much of the time, cost is a prohibitive factor because low cost is one of the factors that led to the construction of the relatively inexpensive fused tap circuit in the first place.

This COMTRADE file shows that short-circuit current magnitudes do not always match the bolted-fault calculations performed in power system studies. When selecting transformer differential setpoints, it is important to consider that the transformer windings and the conducting medium in the fault introduce impedance in the faulted circuit and therefore limit short circuit current. Being overly conservative in selecting a transformer differential pickup could result in a failure to operate the differential, prolonged fault duration and greater load loss than would have otherwise occurred if the 87 pickup were set more sensitively.

REFERENCES

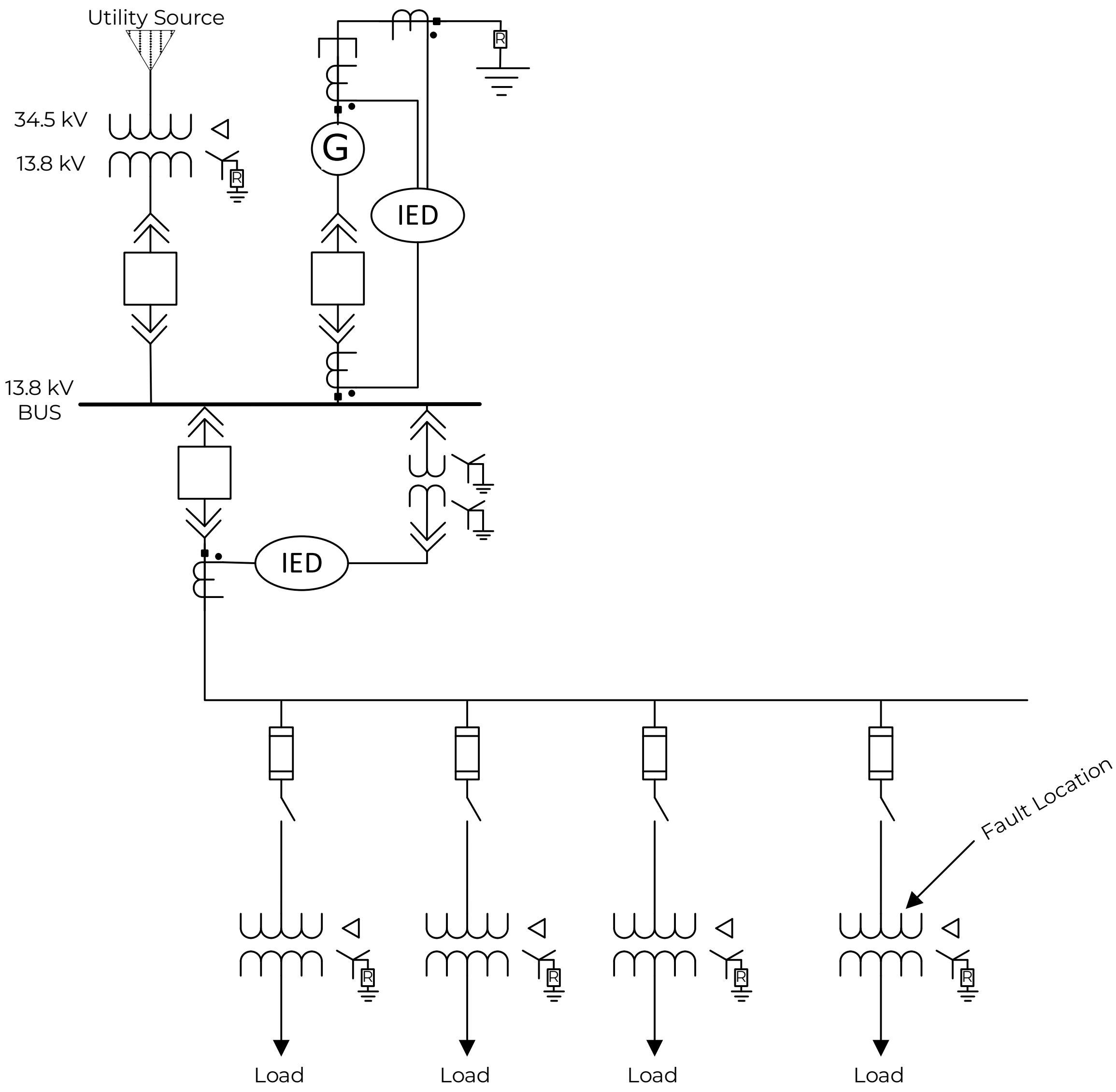
[1] IEEE Standard 32-1990, IEEE Standard Requirements, Terminology, and Test Procedures for Neutral Grounding Devices

[2] IEEE C37.41-2008 - IEEE Standard Design Tests for High-Voltage (>1000 V) Fuses, Fuse and Disconnecting Cutouts, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Fuse Links and Accessories Used with These Devices.

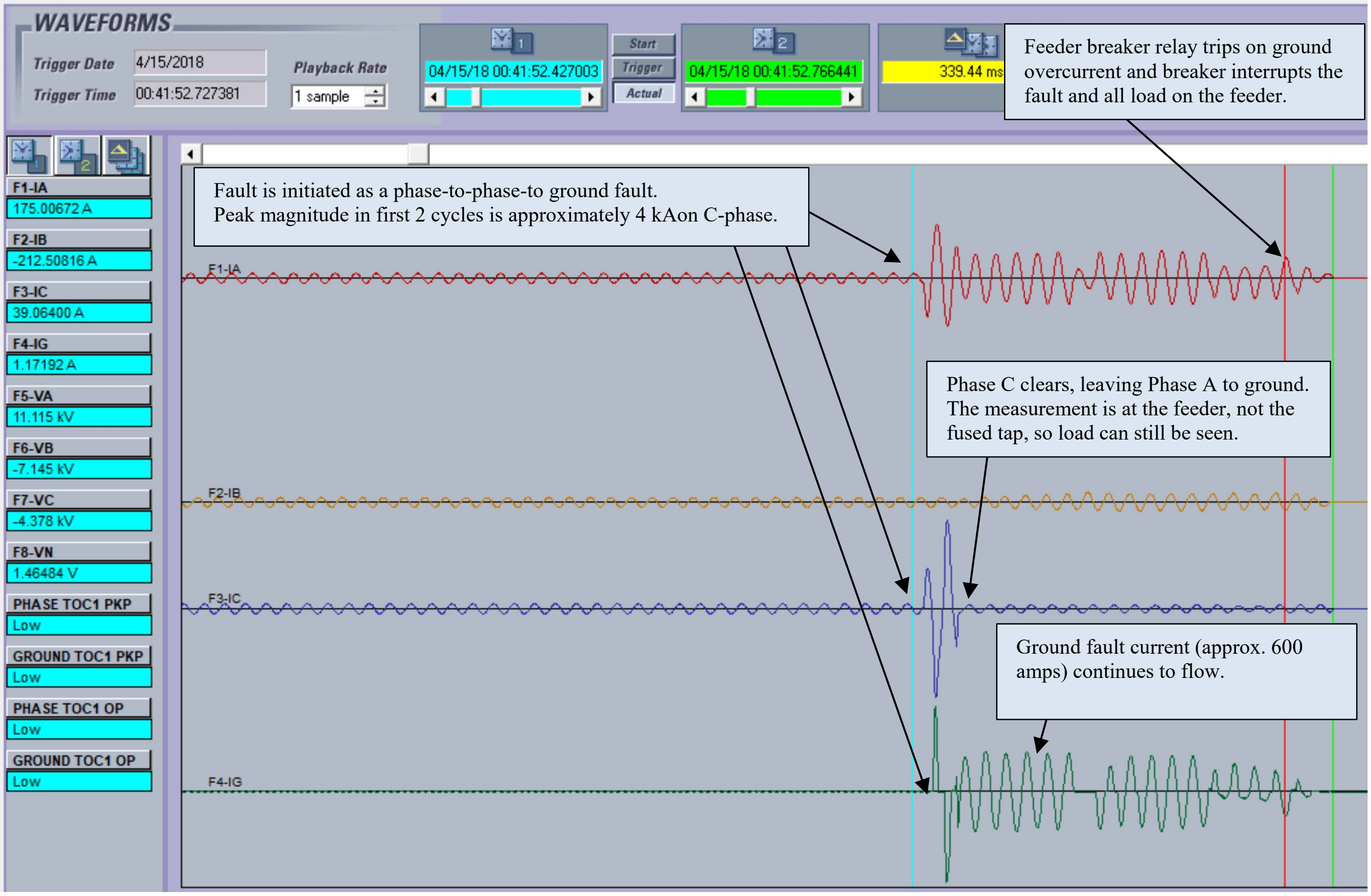
[3] IEEE Std C57.130–2015, IEEE Guide for the Use of Dissolved Gas Analysis Applied to Factory Temperature Rise Tests for the Evaluation of Mineral Oil-Immersed Transformers and Reactors.

Matt Proctor is currently a Managing Partner of Root3 Power. Previously he was a Senior Technical Sales Staff Manager for GE Grid Automation specializing in power system studies and protective relay applications. Matt has applied protective relays in applications ranging from 500kV utility substations to 480V industrial distribution and from electromechanical relays to modern digital relays using IEC61850. Matt earned Bachelor of Science in electrical engineering from Louisiana State University in Baton Rouge, LA in 2001 and an MBA from LSU in 2005. He has been working in the electrical power field in various capacities since 1997 and is a registered professional engineer in the state of Louisiana. He can be reached at Matt.Proctor@Root3Power.com.

Appendix A: System One-Line



Appendix B: Feeder IED COMTRADE



Trigger Date 4/15/2018

Trigger Time 00:41:52.727381

Playback Rate 1 sample

04/15/18 00:41:52.427003

04/15/18 00:41:52.766441

339.44 ms

F1-IA 175.00672 A

F2-IB -212.50816 A

F3-IC 39.06400 A

F4-IG 1.17192 A

F5-VA 11.115 kV

F6-VB -7.145 kV

F7-VC -4.378 kV

F8-VN 1.46484 V

PHASE TOC1 PKP Low

GROUND TOC1 PKP Low

PHASE TOC1 OP Low

GROUND TOC1 OP Low

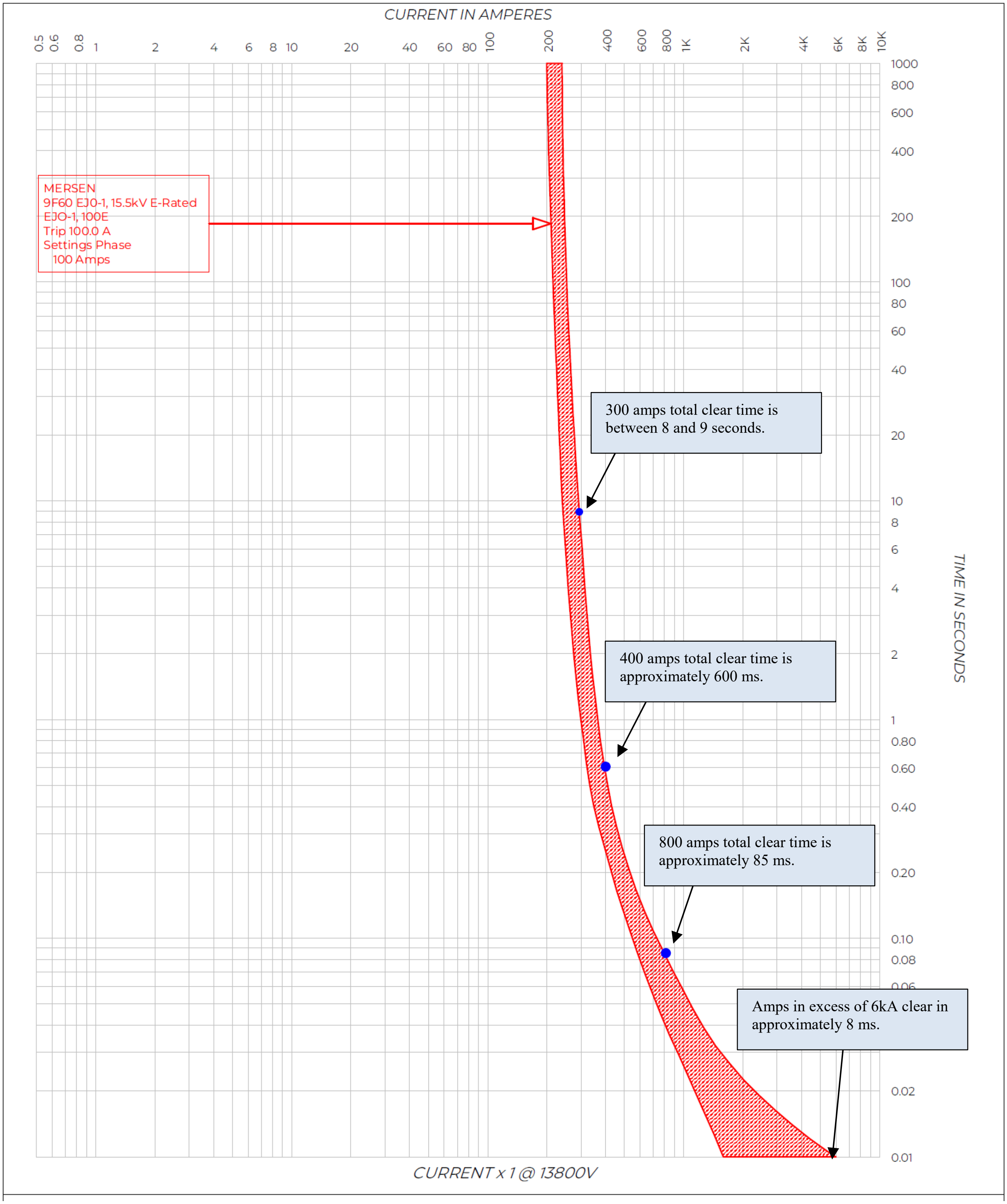
Feeder breaker relay trips on ground overcurrent and breaker interrupts the fault and all load on the feeder.

Fault is initiated as a phase-to-phase-to ground fault.
Peak magnitude in first 2 cycles is approximately 4 kAon C-phase.

Phase C clears, leaving Phase A to ground. The measurement is at the feeder, not the fused tap, so load can still be seen.

Ground fault current (approx. 600 amps) continues to flow.

Appendix C: 100E Time vs Current Curves



300 amps total clear time is between 8 and 9 seconds.

400 amps total clear time is approximately 600 ms.

800 amps total clear time is approximately 85 ms.

Amps in excess of 6kA clear in approximately 8 ms.