

Differential Protection Misoperation Mitigation Strategies in a Digital Substation

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Abstract

Stability and sensitivity of differential protection (87) have been a topic of continuing interest for protection and control (P&C) engineers over the years. The misoperation of 87 function due to CT saturation, incorrect vector matching, incorrect current ratio and zero sequence current compensation are the usual challenges in a differential scheme. In differential protection schemes, such as transformer differential (87T) and low impedance bus differential (87B), loss of one of the contributing CTs may result in misoperation, especially under system normal condition or out-of-zone fault conditions.

Several mitigation techniques have been developed over the years to improve the stability of differential protection without compromising the sensitivity of protection to clear a fault within the protected zone. These mitigation techniques are equally valid in a digital substation. However, there is a new element to be considered to ensure the stability of 87 function in a digital substation. In the digital substation architecture, the analog current measurements from the current transformers (CT) are digitized using the substation merging units (SMU). The sampled values (SV) from the SMU are fed to the 87-protection algorithm for monitoring and protecting the equipment within the zone of protection. Furthermore, the SV streams are time synchronized to a precision clock with microsecond accuracy per IEEE 1588 PTP standard. One of the major benefits of IEC 61850 standards based digital substation design is the ability to continuously monitor the health and availability of the SMU, protection functions and the redundant communication network. Any component failure is immediately detected, and alarms are generated to proactively notify the operator.

How should the 87-function behave in the event of bad quality of an SV data stream or in the event of a loss of time synchronization should be a matter of careful consideration during P&C scheme design. In a digital substation differential protection scheme, the loss of any contributing MU causes the same outcome as losing a contributing CT. Therefore, adequate mitigation and back up protection scheme need to be included in the P&C design. This paper discusses the strategies implemented in a real world 345kV/34.5kV digital substation P&C scheme design to provide adequate protection to the power transformer and the substation busbar.

I. Introduction

In traditional protection schemes including Transformer Differential (87T) and Low Impedance Bus Differential (87B) have been well developed as well as many available techniques on the detection and mitigation methods to cope with CT failure conditions contributing to differential schemes. Similarly in digital substation implementation where Merging Units (MU) are utilized as analog-to-digital converters located adjacent to primary apparatus in outdoor substation yard such as circuit breakers, power transformers, CTs, and PTs, etc., careful analysis for MU failure conditions must be addressed in order to prevent protective relays to misoperate when MU failure occurs.

The scope of this paper is to describe the components of digital substation, MU failure detection, and proactive mitigation methods implemented in a real life project.

II. Evolution of Digital Substation

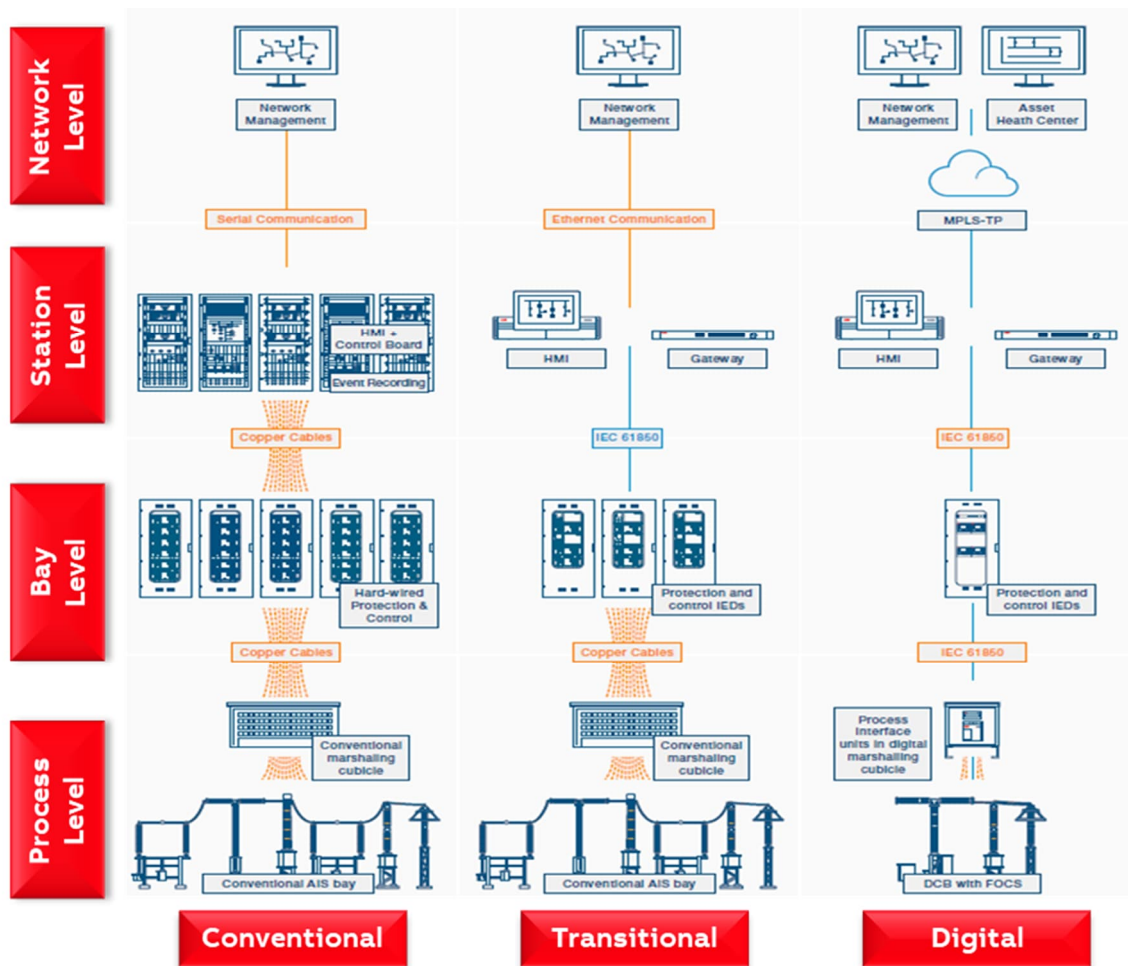


Figure 1: The Evolution of Digital Substation

Since its publication in 2004, the global standard IEC 61850 has been gradually accepted at a slower pace in North America. Regardless there are projects adapting the standard have been successfully

implemented and commissioned recently. One of the main objectives of IEC61850 based digital substation transformation is replacing copper conductors between outdoor switchyard and control house with fiber optic cables. To accomplish this objective, Merging Units (MU) are utilized to convert analog signals to Sampled Values (SV) and binary signals to GOOSE messages for Centralized Protection and Control units (CPC) inside the control house.

III. Traditional P&C with Copper Wires

The one line in figure 2 is a typical collector substation. The 345kV line is protected by the line differential function 87L1P and 87L1S which are the main and back-up protection functions. 87T1P is the overall differential protection scheme. 87T1S is the back-up protection for the transformer T1. 87B1 is the 34.5kV bus differential protection scheme. Each 34.5kV feeder is protected by its respective 50F relay.

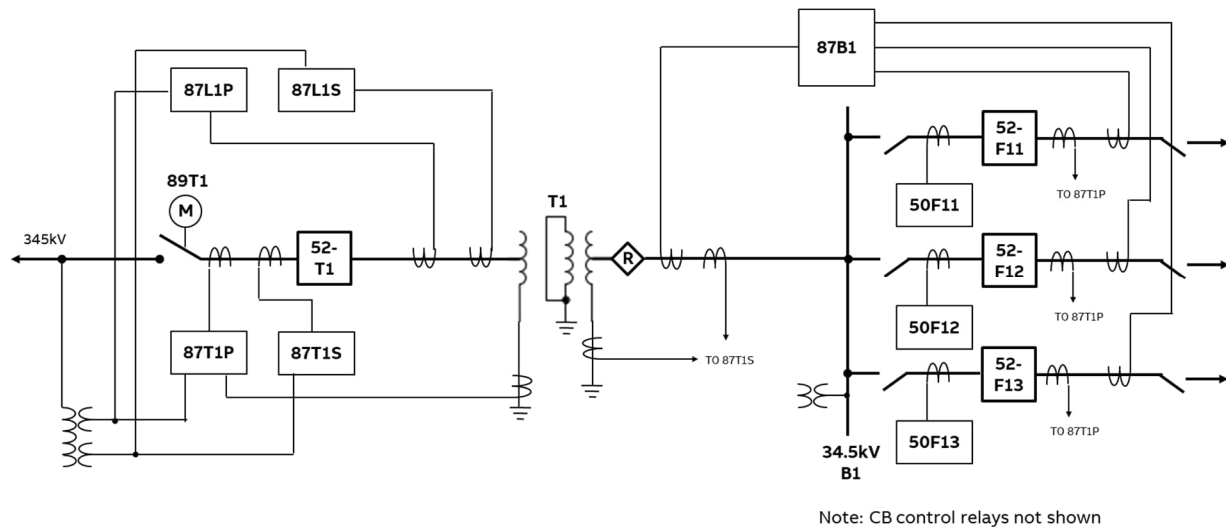


Figure 2: Conventional Protection Diagram

IV. Digital P&C Design with Local Process Interface Units

The digital P&C design is as shown in figures 3 and 4. The protection of the entire substation is performed by a centralized protection and control (CPC) relay. CPC1 and CPC2 are the main and redundant relays configured to operate in a hot-hot mode. Each CPC is configured to perform the line protection, transformer differential protection, bus bar differential protection and the protection of the 34.5kV feeders.

The merging unit (MU) wired to each CT/PT convert the analog signals to IEC 61850 sampled values for its respective protection. The merging units designated by a suffix 1 (for example MU1 – 52T1) feeds the sampled values to CPC1 via the parallel redundancy protocol (PRP) network. Similarly merging units designated by suffix 2 (for example MU2 – 52T1) feeds the sampled values to CPC2 via the parallel redundancy protocol (PRP) network.

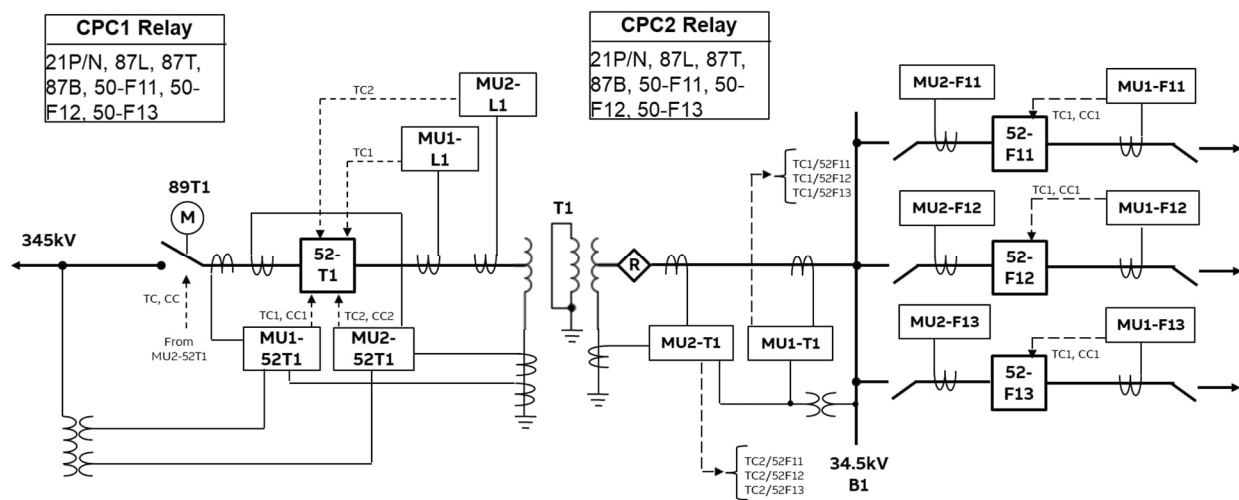


Figure 3: Digital Substation Protection Diagram

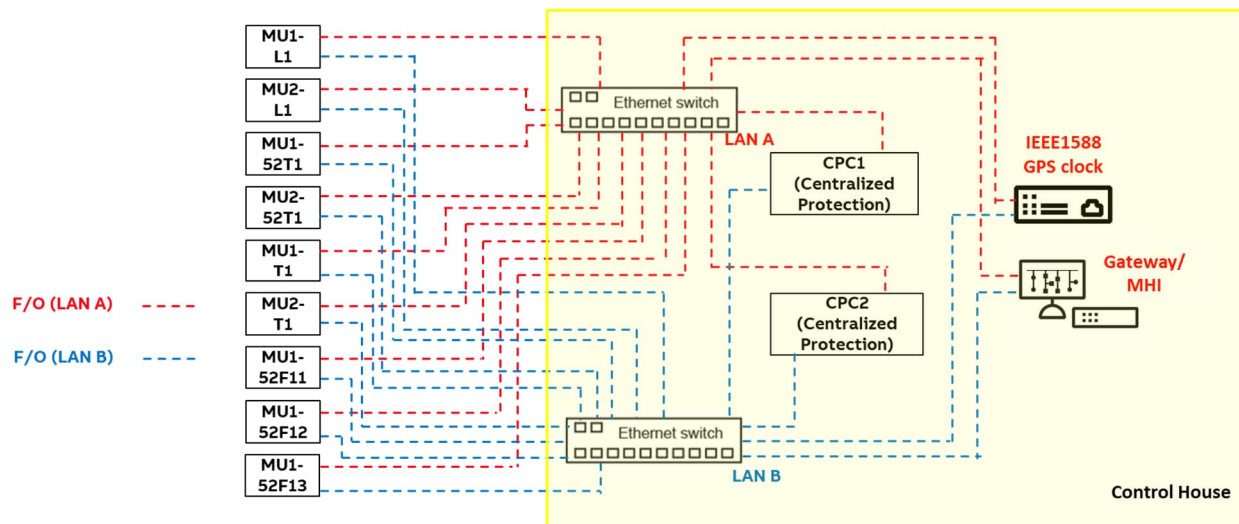


Figure 4: Protection Network Topology at Digital Substation

The merging unit assignment and the corresponding protection functions are listed in Table 1.

Protection Type	Protection ID	Contribution Merging Unit	Target
345kV Line Protection, Primary	21-P/N, 50/51/67-P/N, 59G	MU1-L1	TC1/52T1
345kV Line Protection, Secondary	21-P/N, 50/51/67-P/N, 59G, 79	MU2-L1	TC2/52T1
T1 Transformer, Primary	87T, REF	MU1-52T1	TC1/52T1, TC1/52-F11, TC1/52-F12, TC1/52- F13
T1 Transformer, Secondary	87T, REF	MU2-52T1	TC2/52T1, TC2/52-F11, TC2/52-F12, TC2/52- F13
35B1 Distribute Bus Differential	87B, 50BF (52-F11, 52-F12, & 52-F13)	MU2-T1, MU1-F11, MU1-F12, MU1-F13	TC1/52T1, TC1/52-F11, TC1/52-F12, TC1/52- F13
F11 Distribute Feeder	50/51/67-P/N, 50BF	MU1-F11	TC1/52-F11
F12 Distribute Feeder	50/51/67-P/N, 50BF	MU1-F12	TC1/52F12
F13 Distribute Feeder	50/51/67-P/N, 50BF	MU1-F13	TC2/F2F13

Table 1: Merging Unit Assignment in Digital Protection

V. Merging Unit Failure Mitigation Methods

A) Tripping of the associated circuit breaker

This mitigation method is only applicable in case of failure of one of the Merging units associated to a feeder breaker. In this case, by tripping the breaker, the feeder is taken out of the differential evaluation, avoiding the creation of a false differential current.

B) Blocking of the protection element

To handle situations where SMV is not available, its quality is not good or there is an issue with time synchronization, the WARNING and ALARM outputs of SMV measurement function blocks must be connected to the application, for example to block a protection function as shown in Figure 5.

The SMV receiver activates the TxTR WARNING and ALARM outputs if any of the quality bits, except for the derived bit, is activated. When the receiver is in the test mode, it accepts SMV frames with a test bit without activating the TxTR WARNING and ALARM outputs.

The TxTR WARNING in the receiver is activated if the synchronization accuracy of the sender or the receiver is worse than 4 μ s. The output is held on for 10 seconds after the synchronization accuracy returns within limits.

The TxTR ALARM in the receiver is activated if the synchronization accuracy of the sender or the receiver is unknown, the difference between the received samples time stamp and the protection relay's time is more than 8 ms, the SMV frame is delayed more than SMV Max Delay or two or more consecutive SMV frames are lost. The output is held on for 10 seconds after the synchronization accuracy returns within limits.

The quality of received SMV is available as outputs in TxTR function blocks and is not propagated directly to protection function blocks along with the SMV measurement values.

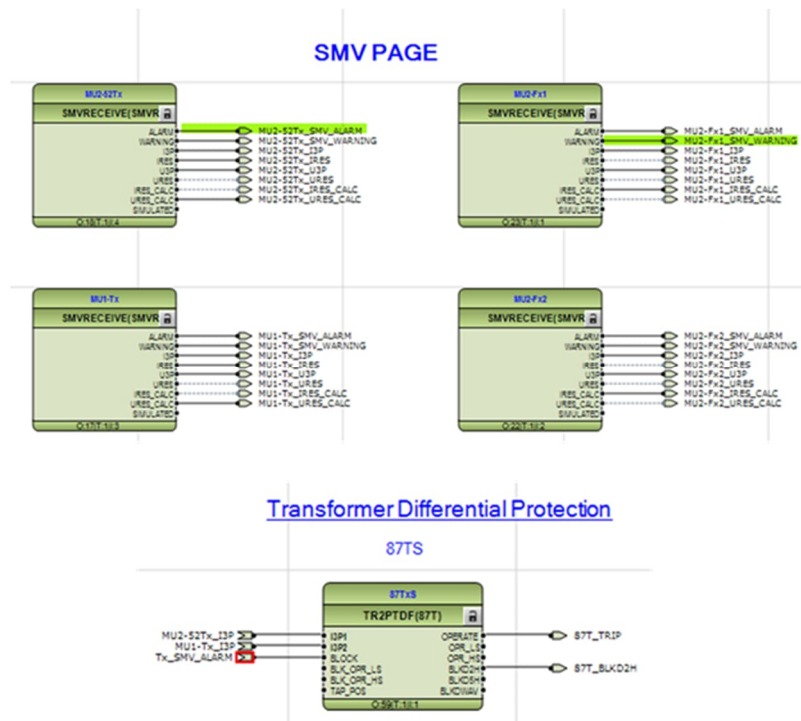


Figure 5: Blocking of Protection function

C) SMV current switching method

The Substation design is done in a way that the Merging units for CPC system 1 are independent of the Merging units of the CPC system 2. This guarantee that even in the event of failure of any of the CPC systems, the integrity of the protection system is not affected.

However, in case of failure of a merging unit associated with either 87T of 87B, since both systems are measuring the same current, one of the mitigation scenarios is have both CPC systems subscribed to all the Merging units, and, in case of failure, perform a current switching.

The current switch function CMSWI performs the switching function between current groups, and it will be triggered by the failure of the merging unit, as shown in Figure 6.

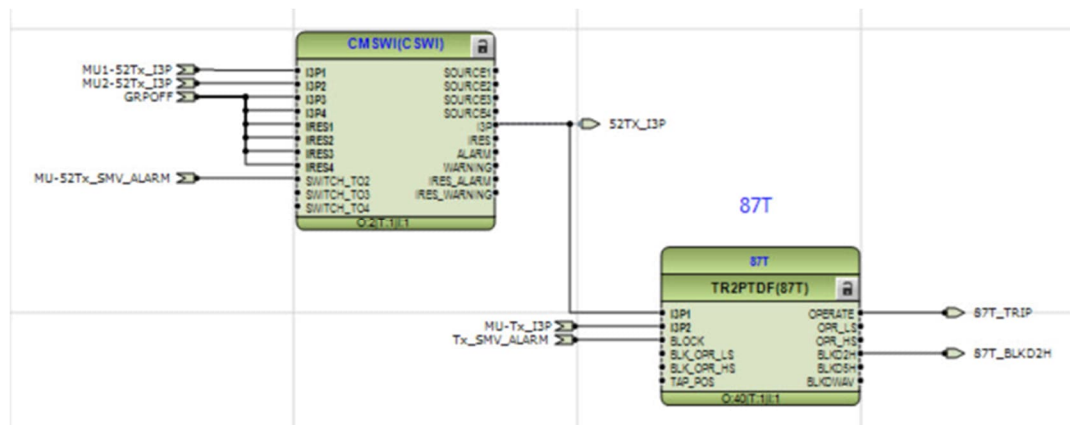


Figure 6: SMV current switching logic

VI. Summary

This section summarizes merging unit failure scenarios used in the differential protection schemes. In the event of a certain MU failure, the action taken for a specific type of fault is listed against each fault.

MU1-T1 failure

Option	Scenario	87T1P	87T1S
Do Nothing	Normal operation	Normal (no trip)	Mis-operation, trips 345kV and 35kV CBs with I-diff setting below 0.5PU
	Transformer Fault	Trips 345kV and 35kV CBs by 87T	Trips 345kV and 35kV CBs by 87T
	35kV Bus Fault	Trips 345kV and 35kV CBs by 87T	Trips 345kV and 35kV CBs by 87B
	35kV Feeder Fault	Trips the associated 35kV CB with directional O/C by 50/51-F1X	Trips the associated 35kV CB with directional O/C by 50/51-F1X
Block 87T1S Function	Normal operation	Normal (no trip)	No trip, 87T1S blocked
	Transformer Fault	Trips 345kV and 35kV CBs by 87T	No trip, 87T1S blocked
	35kV Bus Fault	Trips 345kV and 35kV CBs by 87T	Trips 345kV and 35kV CBs by 87B

	35kV Feeder Fault	Trips the associated 35kV CB with directional O/C by 50/51-F1X	Trips the associated 35kV CB with directional O/C by 50/51-F1X
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MU1-F1X failure

Option	Scenario	87T1P/87B1	87T1S
Do Nothing	Normal operation	Mis-operation by 87T1, trips 345kV and 35kV CBs with I-diff setting below 0.5PU	Normal (no trip) since MU1-T1 is normal
	Transformer Fault	Trips 345kV and 35kV CBs by 87T	Trips 345kV and 35kV CBs by 87T
	35kV Bus Fault	Trips 345kV and 35kV CBs by 87B	Trips 345kV and 35kV CBs by 87B
	Feeder Fault (where its Merging Unit fails)	Trips the associated CB by 50/67	Trips the associated CB by 50/67
Block 87T1P and 87B1	Normal operation	No trip, 87T1P blocked	No trip, 87B1 blocked
	Transformer Fault	Trips 345kV CB with O/C coordination (time delay)	Trips 345kV and 35kV CBs by 87T
	35kV Bus Fault	Trips 345kV and 35kV CBs by 87T	Trips 345kV CB with O/C coordination (time delay)
	Feeder Fault (where its Merging Unit fails)	Trips the associated CB by 50/67	Trips the associated CB by 50/67
Switch to Group 2 with de-sensitized 87T setting	Normal operation	No trip	Normal (no trip) since MU1-T1 is normal
	Transformer Fault	Trips 345kV and 35kV CBs by 87T	Trips 345kV and 35kV CBs by 87T
	35kV Bus Fault	Trips 345kV and 35kV CBs by 87T	Trips 345kV CB with O/C coordination (time delay)
	Feeder Fault (where its Merging Unit fails)	Trips the associated CB by 50/67	Trips the associated CB by 50/67
	Normal operation	Normal (no trip)	Normal (no trip)

Open the impacted 35kV VCB	Transformer Fault	Trips 345kV and 35kV CBs by 87T	Trips 345kV and 35kV CBs by 87T
	35kV Bus Fault	Trips 345kV and 35kV CBs by 87T	Trips 345kV and 35kV CBs by 87B
	Feeder Fault (where its Merging Unit fails)	n/a	n/a

VII. Conclusion

Based on a project implementation and considering the criticality of the assets to be protected, mitigation methods, from least preferred to most preferred, are listed below:

“Do Nothing” option is not recommended and not considered for protection implementation.

“Switch to Protection Group 2 with Desensitized 87T1P Pickup setting” option can be considered in systems with single redundancy system lacking redundant merging units and/or protective relays. It is not recommended either.

“Open the circuit breaker under with impact of MU failure” option is recommended but less preferred than blocking the differential protection of the affected CPC system, because unnecessarily open a healthy feeder.

“Block the Associated Differential Function” is the current implementation in an active project. Primary and secondary differential protection systems are covering up each other for MU failures. Note that under 35kV feeder fault, the 345kV GCB will eventually trip as a backup protection with time delay – which meets expectation of protection coordination. However, by probability the failure should have been recognized with dispatcher corrective action prior to waiting for feeder fault to happen.

“SMV current switching” is the preferred mitigation method as it allows both CPC systems running, even in case of a Merging unit failure.

VIII. References

- [1] Nayan Shah, Murali Kandakatla, and Juha Ylinen, *Advanced CT Supervision Method for Transformer Differential Protection System*.
- [2] ABB's *SSC600 Technical Manual*, Document ID 1MRS758921.
- [3] L. Sevov, J. Cardenas, and Y. Sun, *CT Failure Detection for Differential Protection Applications*.

IX. About the Authors:

Vincent Duong, P.E., PMP, currently holds a Digital System Architecture Director position in the Digital Solutions Center group at ABB. He received his BSEE degree with Power System Specialization from the University of Alberta in Edmonton, Canada; and both MBA and MS in Operations and Project Management degrees from Southern New Hampshire University in Manchester, New Hampshire. Vincent has spent most of his career in critical generation, distribution and transmission protection, controls, and automation engineering, including overall system architecture, modeling, study, design, and system disturbance analysis. He is also actively involved in customer training and power system protection-coordination instruction. He is a Senior IEEE member, a registered Professional Engineer of New Hampshire, and Project Management Professional of Project Management Institute (PMI).

Eduardo Colmenares is a Senior Project Lead Engineer for ABB Digital Solutions Center with over 36 years of experience in the field of Protection and Control. He has been working for ABB US since 2010. Previously, he worked for 15 years in ABB Venezuela where he held several positions including Country Service Manager, BAU Manager for Protection & Substation Automation, BAU Manager for Power Generation and BAU Manager for Utility Communications. Also, he worked 5 years for an Electric Utility with a focus on protection and control. Eduardo has authored or co-authored several papers for Relay conferences. Eduardo has an Electrical Engineering degree from Universidad de Los Andes, Merida, Venezuela in 1987.

Joe Xavier currently serves as the Product Manager for ABB Electrification - ANSI Digital Substation and Flexitest Products. With over three decades of experience in power system protection, automation, and control applications, Joe has been involved in a wide range of responsibilities including product management, marketing and sales management, business development, application and training. He has authored, co-authored, and presented several technical papers on Protection, Automation & IEC 61850 applications and is an active member of IEEE PES – PSRC and PSCC committees. Additionally, Joe is a USNC designated member to IEC TC57-AG22.

Leemen Weaver has been with NextEra Energy for 13+ years. In his current role as a Senior Project Manager in Engineering for the Engineering and Construction Division, Mr. Weaver serves as an applications manager specializing in Protection & Control design, Remote Terminal Unit and SCADA design, metering design, and provides project support to design, implement, and resolve construction issues prior to the commercial operation of an asset, which requires identifying problems during the execution phase, as well as performing testing verifications or performance testing to prove the capabilities of the facility prior to turnover to operations. Mr. Weaver collaborates with project teams to minimize risk and guide solutions to meet project deadlines. He leverages his electrical engineering and

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