A Novel Technique to protect Phase Shifting Transformers: Comparitive Analysis

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***Abstract*— Phase Shifting Transformers (PST) are extremely complex and expensive equipment, designed to control the power flow in power systems. Such a complex device demands unique schemes to overall protect it. The device itself has been analyzed in detail in various cases and today a workable protection scheme is generally implemented by almost every PST user as dictated in IEEE C37.135. This scheme requires several measurement CTs with many of them buried inside the transformer core.**

The difficulties associated with such a scheme are multi-dimensional, ranging from design problems, complex settings engineering, manufacturing issues, not to mention the operational and maintenance constraints.

This paper will introduce a novel, much simpler approach to incorporate a numerical relay-based protection scheme for PSTs. It will provide a full description of how the function works and will summarize its benefits. A quick comparison with the existing technique will also be provided.

The paper will also include results from the testing performed in a utility operations lab using existing protection scheme devised for an in-service PST and will present a comparative analysis on the two schemes of protection, clearly highlighting the key factors that sets apart the new scheme.

I. INTRODUCTION

A utility transmission system is a complex network of feeders interconnected to other equally complex networks of the neighboring utilities. These transmission feeders carry power from sources of generation to loads with the flow on each transmission feeder determined by their relative impedance. Since the level of generation and customer demand changes over the course of the day, the power flow on these transmission feeders changes consequently and are not always consistent with their ratings. Phase angle regulators give a means to control the flow of real power on the transmission system feeders to accommodate for this need.

A phase angle regulator (PAR), phase-shifting transformer (PST), or quadrature booster are the recognized names for a special form of transformer used to control the flow of real power on three-phase electric transmission line, where the sending and receiving ends have no less than two parallel connections.

The operating principal of the PST is based on the power flow equation (1):

$$P_R = \frac{V_S V_R}{X} \sin\delta \qquad (1)$$

Where
P_R is the Real Power
V_S is the Sending Bus Voltage
V_R is the Receiving Bus Voltage
X is the Series Reactance of the transmission line
δ is the angle between the two Voltages

Since power flow is a function of the angle between the voltages at the two ends of a line, the flow on the line can be controlled by changing the angle. This is the purpose of phase angle regulators. In the absence of PSTs, the power flow between any two points in a system will follow the path of least electrical impedance, according to the laws of physics as shown in Fig 1.

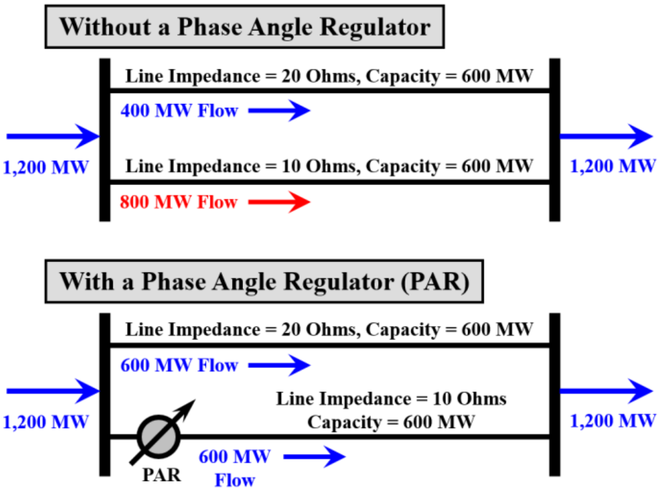

Fig 1: Power Flow control in a Network

Phase-shifting transformers have been in use for many years for control of power flows in transmission lines. The most commonly used types can be classified into the groups shown below:

1. symmetrical - non symmetrical (based on the magnitude of the voltage between the source and load side)
2. quadrature - non quadrature (based on the presence of tap changer)

When it comes to the construction design, the PSTs can be classified as

1. single core - two core (based on the number of transformers used)

2. single tank - two tank (dictated by the space availability)

From an operational point, PSTs can have

1. A fixed or variable phase shift under load.
2. The quadrature booster voltage that can be reversible

Each of the types mentioned above are different construction wise and provides varied level of controls to operate the PAR itself. The use and difficulties of such designs are exhaustively explained in the C57.135 IEEE guide [1].

The protection of Phase Shifting Transformers (PST) depends on its type, construction, CT availability and location. Providing an adequate protection for such a complex device is a challenging task for a protection engineer. In this paper we will narrow the discussion by considering a widely used classic PST with symmetrical, two cores - two tanks design (series unit and exciting unit), with on-load tap changer (LTC). The secondary of series transformer is delta connected, the excitation windings are connected as wye-wye as shown in Fig 2.

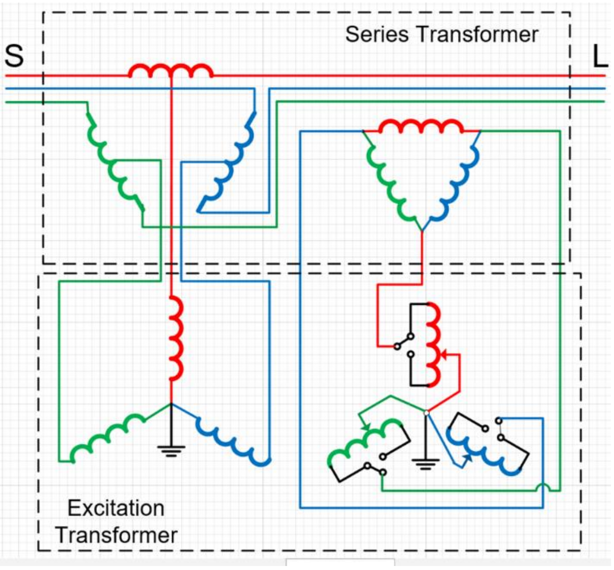

Fig 2: Symmetrical Two Core PST

II. EVOLUTION OF PST PROTECTION SCHEMES

A. Old Electromechanical Schemes

In the era of electromechanical relays, each device performed only one function, mostly on a single-phase basis. And when it came to PST protection such a design required many such boxes. One such design for a 345kV PST is shown below in Fig 3.

The protection scheme consisted of the following:

- One set of differential relays with percentage and harmonic restraint provided protection for the series regulating windings – 87P.
- One set of differential relays with percentage and harmonic restraint provided overall protection for the series and excitation windings – 87S.
- One set of phase over-current relays provided backup over-current protection for the regulator – 51S.
- One neutral ground over-current relay provided ground over-current protection in the neutral of both the exciting and regulating windings – 51N-1 and 51N-2.
- The exciting winding neutral ground over-current relay was supervised by a harmonic restraint relay. The harmonic restraint provides security against false tripping from magnetizing inrush current when energizing the regulator – 51N-2S.
- One set of phase over-current relays provided out of step protection for the phase angle regulator if the two tap changers become two or more taps apart – 51TC.
- Four sudden pressure relays: one on the series windings transformer, one on the exciting windings transformer and one relay in each selector compartments regulator winding. These relays detected a sudden increase in the tank internal pressure and actuated a snap-action switch located on the transformer.
- Three fault-detecting relays, one for each phase, supervised the operation of the sudden pressure relays and provided security against false tripping for external faults – 51FP.

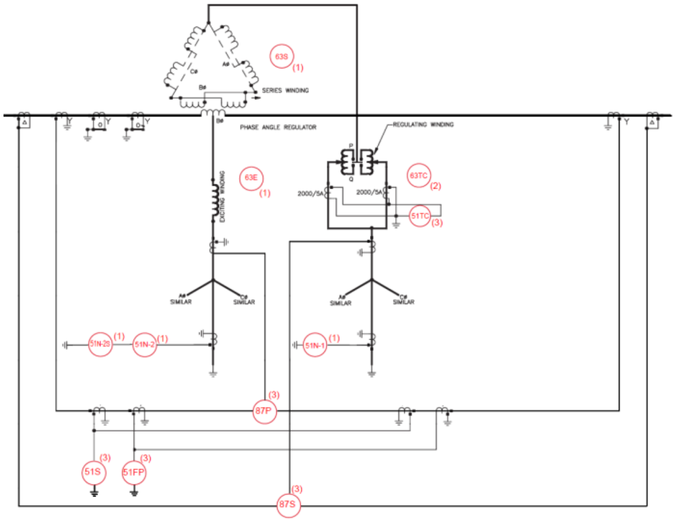

Fig 3: Electromechanical relay-based scheme

In total such a scheme required 22 relays, including Sudden Pressure or Buchholz Relays in each main tank and LTC for detection of low current magnitude turn-to-turn faults.

It must be also noted that in this arrangement the two differential protections are not fully redundant and two sets of CTs at source and load sides of primary series winding is a must due to wye-connected CTs used by 87P and delta-connected CTs used by 87S

When using electromechanical relays choice of CT ratios, CT connections and CT polarities play a very important role.

B. *Currently Available Schemes*

Currently there are various techniques available in the market to effectively protect the PST. The most typical scheme uses two sets of differential protection, be it on two separate relays or in one relay depending on the availability of required analog inputs and multiple instances of the protection function itself. One to provide protection of the primary windings of the series and excitation cores which is based on Kirchhoff's Current Law (KCL) and the other to provide protection of the secondary windings of the series and excitation cores which is based on the Ampere turns Balance (ATB) [2]. This scheme is shown in Fig 4. This next generation microprocessor-based PST protection merely replicated the electromechanical relay schemes, combining all functions into fewer boxes supplemented with all the built-in microprocessor relay benefits.

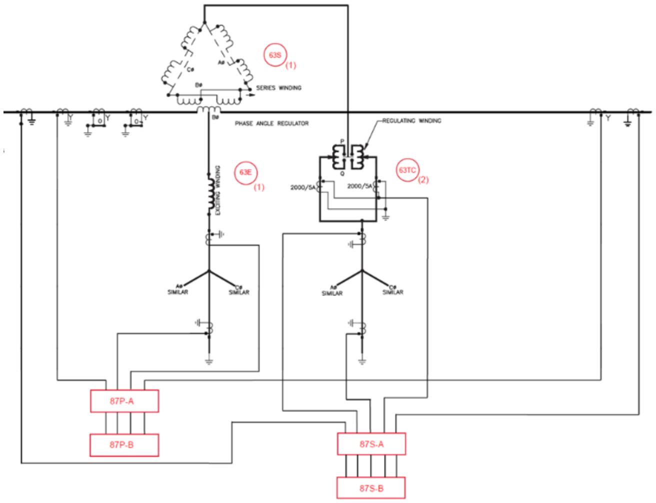

Fig 4: Numerical Relay Scheme

Another technique utilizes the tap changer information to adjusts the operating characteristics of the relay system in response to changing system conditions. Such a concept provides a sensitive and cost-efficient protection for regulating transformers [3].

Another new technique introduces the concept of sequence components. It utilizes both positive and negative sequence-based differentials to implement an overall differential protection. Such a scheme requires voltage transformer (VT) inputs to compensate for the PST operating angles. It uses the same VT information for fault direction detection as well [4].

All these schemes have their own benefits and disadvantages. In the [2] scheme, it was just a replication of what was designed using the technology that was available during the electromechanical relay days. Deploying such a scheme in a digital design introduces additional complexity in computations to calculate the settings. On top of that such a scheme doesn't compensate adaptively for all the PST operational angles. Normally in this design the 87S differential protection used for protecting the secondary windings of the series and the excitation transformer is set to compensate only for the maximum phase angle shift in the PST. Because we do not have the PST operational phase angle information, all the calculations like MVA, base currents are all performed for maximum phase shift. This is the reason why the second differential settings uses the clock settings as Yy6d9 and uses effective MVA, voltage and current settings as explained in [5].

Consider the [3] scheme mentioned, relying on the OLTC information sounds economical but it still provides only an easy methodology for the magnitude compensation but when it comes to phase compensation a lot of computations is required to adapt a traditional differential protection to work correctly.

The [4] scheme introduces a novel scheme, which requires extensive simulation studies to understand the performance of a PST under different fault conditions to effectively set the relay.

Ignoring the engineering difficulties involved in properly setting up such protection schemes, there are many other constraints like computational difficulties of relays which forces users to use more than one relay to completely protect a PST. Not all relays can accommodate both 87P and 87S in the same box. In the operational front, testing such a scheme introduces more difficulties. Most likely such a scheme is tested only to prove the settings. Because it becomes computationally intensive to test and prove all the operating conditions of the PST with such multi-box, multi-function schemes.

In [6] it is mentioned that with the advent of technology, there is a possibility to effectively protect a PST with another simple technique. Such a scheme requires a real-time magnitude and phase compensation to accommodate all the operating conditions of a PST. This scheme is shown in Fig 5.

Such a scheme requires at least a single-phase VT connection on both the source and the load side of the PST to perform the protection. But such a scheme is not constrained by the PST construction design and doesn't require any extensive study/ calculations to setup the relay. All the settings needed to set such a relay is directly taken from the nameplate details of the PST. In addition, testing such a relay becomes very straight forward. This scheme removes the need for buried CT's which has its own constraints as explained in [7].

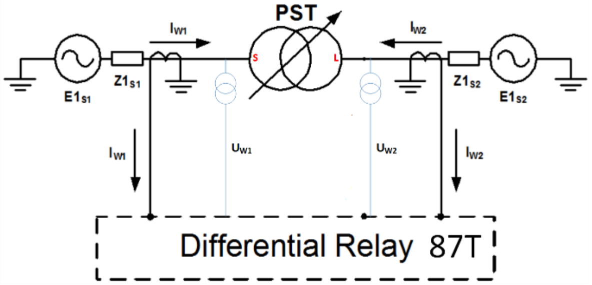

Fig 5: Arbitrary PST protection[6]

III. MODERN PST PROTECTION SCHEME

The requirements for the PST protection have changed over time. Today there is a lot of emphasis on the NPCC requirements for the Bulk Power system protection Criteria which states:

> “*5.2 Criteria for Dependability*
>
> *5.2.1 Except as identified otherwise in these criteria, all elements of the bulk power system shall be protected by two protection groups, each of which is independently capable of performing the specified protective function for that element. This requirement also applies during energization of the element.*
>
> *5.2.1.1 The failure of a merging unit shall not lead to the momentary or permanent loss of more than one protection group per element.*
>
> *5.2.2 Except as identified otherwise in these criteria, the two protection groups shall not share the same component. If the two protection groups share a redundant component in order to achieve improved reliability, the galvanic isolation and physical separation of the two protection groups shall not be compromised.*” [8]

In a traditional IEEE scheme [1] as shown in Fig 6,

- 87P uses CTs: 1+2+3 and it operates like “busbar differential” (it requires 3-Ph buried CT No 3)
- 87S uses CTs: 1+2+4 and its operates as “transformer differential” based on series transformer ampere-turn balance principle (it requires 3-Ph buried CT No 4)
- The neutral point CTs 5 and 6 are used for EF protection

Bushing CTs 1 and 2 usually have multiple cores that can be used for the two protection groups but CTs 3 and 4 are usually buried inside the transformer tank and are limited by space constraint to accommodate multiple cores. In most of the cases users end up sharing the CT’s between the protection groups which defeats the compliance with NPCC requirements. Also, when performing maintenance, both lines of protection needs to be taken out of service to conduct the relay calibration tests.

The modern protection utilizes only the bushing CTs 1 and 2 on the source and load side respectively. It also requires 2 VTs at the same locations for large phase shifts. The neutral point CTs 5 and 6 are used for EF protection same as in IEEE scheme. With the availability of VT, we can include additional backup protections like under impedance, directional over-current and POTT scheme to better protect the PST.

To enable differential measurement for phase shifting transformers, it is necessary to extend the measurement for standard 2-winding power transformers by measuring on-line the transformation ratio and phase angle shift. This would permit differential measurement for any phase shifting transformer, regardless of its construction (symmetrical or asymmetrical; single-core or double-core). Hence sometimes such a scheme is called as the self-adaptive protection scheme. The equations governing the magnitude and phase angle relationships between the voltage and current sequence components during no-load and loaded conditions are explained in [6].

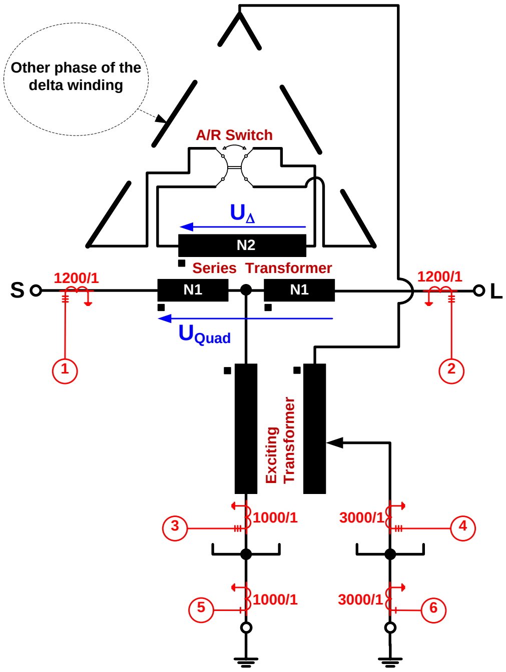

Fig 6: Traditional IEEE Scheme [5]

The new PST protection under no-load conditions, uses the positive sequence voltages from the source and load side to calculate the magnitude and phase compensation. Under load conditions it uses the positive sequence voltages for magnitude compensation and the corresponding currents for phase compensation. During our test comparison, we did simulate these conditions to check the stability of this algorithm. It was found that the algorithm worked fine for staged phase shifts in a smooth manner and compensated in real time for each phase angle shift.

Enhancing the performance of the standard differential protection was achieved by combining its good properties with those obtained from a negative sequence directional comparison measurement. For an external fault, the negative sequence contributions from each side of the transformer are in opposite direction, with the opposite being true for an internal fault, i.e. the negative sequence contributions from each side of the transformer are in the same direction. This negative sequence measurement not only discriminates between internal and external faults but can also detect minor faults with very high sensitivity and speed. Turn to turn faults result in a source of negative sequence current due to asymmetry in the number of turns across the phases of the faulted winding. Such internal winding turns to turn faults can be detected with high sensitivity based on the direction of flow of the negative sequence currents. The negative sequence function provides the same sensitivity to phase shifting transformer turn to turn faults as the traditional differential function applied to standard power transformers.

IV. TEST BED DETAILS

The test bed included two numerical relays, one operating on the traditional IEEE scheme and the other used the new self-adaptive differential protection for power transformers as mentioned in [6].

As a preparation for the test, the following steps were followed:

1. An existing PST within the installed base was chosen and its name plate details were used as basis for calculating the settings for both the schemes.
2. For the traditional IEEE scheme, in order to calculate the settings for the 87P function, the MVA rating and CT polarity were the only details needed.
3. For the traditional IEEE scheme, in order to calculate the settings for the 87S function, the equations from [5] were utilized.
4. For the new self-adaptive scheme, the nameplate details from the PST regarding the minimum and maximum phase shift and the corresponding voltage magnitudes were all that was needed to setup the relay. No extra calculations were needed.
5. CAPE™ short circuit study analysis was used to simulate faults in the system, both internal and external to the PST. To simulate sensitive turn to turn faults 1pu negative sequence faults were simulated internal and external to the PST. The results obtained were used to calculate the required buried CT current contributions for the traditional IEEE scheme using the equations mentioned in [2].
6. All the currents were simulated using a traditional test set with 2 sets of high current outputs and 2 sets of voltage/ current outputs.

The disturbance records collected from the two relays were used to analyze the performance of the protection scheme for all the faults injected.

A. Test Results

The goal of testing these protection schemes were not to try make the argument that one is fundamentally better than the other. It was to understand the behavior of each of the schemes when put to test under conditions close to the real-life scenarios. Because PSTs' are dynamically controlled devices, testing protection schemes just to prove the settings alone is not enough. There is a need to understand the performance of these schemes under a no-operation condition, for say a through fault. Added to these complexities is the external conditions like saturation of bushing CT's on the series transformer for external fault conditions. Since most modern relays today are equipped with some form of security against CT saturation and block the differential functions, this topic was not studied as a part of this paper's scope.

For both the conventional IEEE scheme and the new self-adaptive scheme the following faults were simulated:

- 3ph through faults in neutral, mid-tap advance, maximum advance and maximum retard positions of the OLTC.
- close-in 1p.u negative sequence faults in neutral and maximum advance positions of the OLTC.
- Internal B to C phase faults on the exciter secondary in both neutral and maximum advance tap positions.

Below are the comparison results of the two schemes for internal and external faults.

B. External Faults

Though both the IEEE scheme (87P and 87S) and the self-adaptive scheme (87PST) were stable for through faults external to the PST, when the differential currents were plotted on the differential characteristics, each of them occupied different spots in the curve as shown in Fig 7. The choice of settings for these functions determine the movement in the location for 87P and 87S. it must be noted that only 87PST truly represent the actual differential currents as seen by the PST.

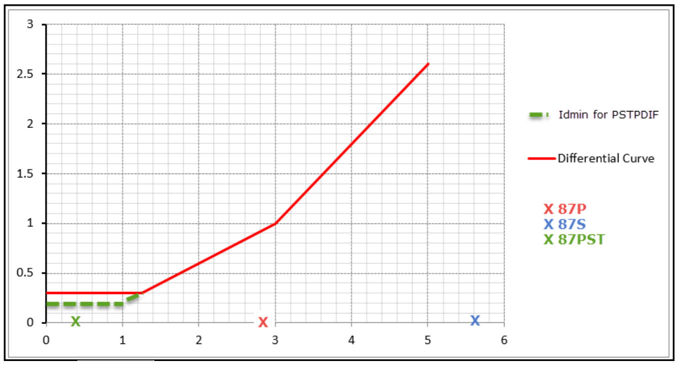

Fig 7: External Faults

C. Internal Faults

To simulate a close-in turn to turn fault, a 1 p.u negative sequence fault was simulated on the secondary of the excitation winding. From the DFRs the currents calculated by the different functions are shown in Fig 8. It has to be noted that even in this case only the 87PST negative sequence differential function replicates the differential fault currents. All these results only reiterates the previous conclusions mentioned in [1] that the traditional IEEE scheme is not very sensitive for turn-turn faults.

Another point to note is, when testing the IEEE scheme, when 87P was tested 87S was switched off and vice versa, to avoid mis-operation because of the inability to simulate all the contributing currents at the same time in a single testset.

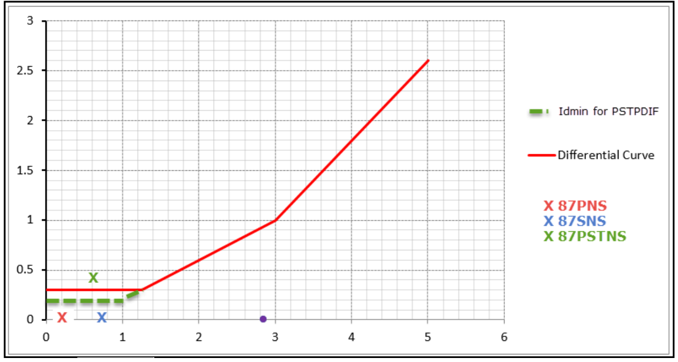

Fig 8: 1p.u Negative Sequence Internal Fault

V. CONCLUSIONS

Reading all the literature available for the different PST protection schemes and testing two of those schemes, the following was inferred:

- The traditional IEEE scheme requires a large amount of engineering work to model the PST for any short circuit study.
- Testing the traditional IEEE schemes requires access to the mid-point primary series winding CT currents to test the 87P function, these values were not readily available from any short circuit models of the PSTs and had to be calculated for each phase shift from the equations in [2].
- Testing such a scheme in a multi-box arrangement (87P and 87S in two different boxes) required multiple testsets. Having the functions in the same box reduced the complexity but still at least 4 sets of current sources were needed in a test set to perform the full scheme test.
- Testing the two differential functions 87P and 87S individually do not provide the complete operating behavior of this protection scheme. This was clearly visible when turn-turn faults were simulated in the excitation windings.
- The self-adaptive PST protection scheme provides a simpler alternative to calculate the settings and test the relay in addition to providing a secure overall protection for the PST.
- With no requirement for buried CT's, testing the PST for all its operational phase shift was much easier with the new scheme.
- Since the protection function is self-adaptive for any phase shift, the minimum pickup settings can be set more sensitive to pickup for turn to turn faults.

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VI. BIOGRAPHY

Olga Omelchenko earned her bachelor's degree from Leningrad Power Engineering College, continued her education in Saint Petersburg State Polytechnic University majoring in Electrical Power Stations, and received her MS in Electrical Engineering from North West State Technical University. During her career in Russia she worked as relay protection technician at Kola Nuclear Power Station, continued as relay protection engineer in utility company LenEnergo Power Network. After moving to USA, she joined Alstom T&D, where she worked for seven years, and later worked for system integrator company Unelsys Inc. in Pennsylvania. Last five years she has been with Con Edison, New York as a Senior Protection Engineer.

Grey Kingsley graduated from the City College of New York in 2015 with a Master's degree in electrical engineering. He started working at Consolidated Edison as an intern in 2014 and has held various positions throughout the company since then. Since 2017 he has been an engineer in the Protective Systems Testing department where he provides support for the commissioning, maintenance and troubleshooting of microprocessor based protective relays.

Bharadwaj Vasudevan graduated from North Carolina State University with a Master's degree in power systems in 2013 and joined ABB as an Application Engineer for Protection, Control and Automation systems. He started his career in power systems with Areva T&D India Ltd in 2009. He has worked on various EHV substation projects throughout India. Currently he is working out of New Jersey as the Regional Technical Manager for North East US. In the last 6 years he has been involved in numerous IEC 61850 projects across the US helping utilities to adopt the new engineering standard.

Mike Kockott joined ABB Inc. in Raleigh, North Carolina as a Senior Applications / Product Specialist in November 2011. Prior to relocating to North America, Mike worked as a Senior Applications Specialist / Senior Regional Technical Manager for 12 years at the SA Product factory in Västerås, Sweden. Before joining ABB AB in Sweden in January 2000, Mike was Senior Consultant, Protection (Transmission) at Eskom, South Africa. Mike joined Eskom as a training engineer in 1983, and rose to Protection Design Manager, before switching to Senior Consultant. Mike graduated from the University of Cape Town with BSc (electrical engineering) degree (with honors) in 1980.