Back to the Table of Contents

Perspectives on Substation Design Based on Functionality of Modern Relays

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***Abstract*: Increased functionality in modern relays can yield benefits in the design of the primary system. For example, with multi terminal differential protection, utilities might choose to convert their existing two terminal transmission line into three or more terminals in their networks without the need for forming new loop-in and out substations or breakers. Modern relay technology allows utilizing smaller or existing CTs of various specifications without need for installation of new CTs. The latest IEC61850 allows calculation of currents in various links in the bus bars without fear of overloading the bus, optimizing the design. High speed protection algorithms and Wide Area Measurements (WAM) allow optimized system stability and loading conditions. The developments have changed the way the primary systems are perceived and designed, resulting in savings in investment and running costs and improved operational flexibility.**

***Index Terms*—Protective relaying, distance measurement, differential protection, substations, power system protection, power system transient stability**

I. Introduction

The introduction of microprocessor in protection engineering field has helped achieve a significant progress. So much so it has started modifying some of the topography of the primary power system itself. This paper highlights a few areas of rapid progress in protection and control engineering field which have resulted in changes in the primary systems.

A. *Line Protection and its impact on primary system design*

The transmission line is the most exposed part of the power system with the maximum number of faults. Unlike other power system elements, the transmission line spans considerable geographical distances and hence has been a challenge to detect faults along the line and open the breakers at the ends. The conventional distance protection element provides instantaneous protection without depending on communication means for a good portion of the protected line. However, it typically depends on a single digital information exchange to make an effective high speed protection for faults across the whole length.

The differential protection on the contrary depends on transmitting the analog information from one end to the other end. It effectively applies Kirchoff's current law to decide if a fault is present within a line section or outside. Figure 1 indicates the basics of a line differential protection.

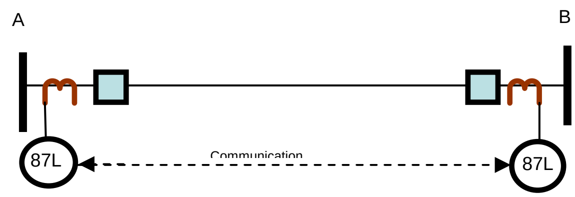

Fig. 1. Typical two terminal line protections

In the classic pilot wire differential protection, the current information in the analog form is transmitted from one end to the other through metallic wires. The limitation is mainly the voltage that would be induced during faults in the power system. Other parameters of the pilot wire including resistance and capacitance etc., also had a bearing on the way the system worked and hence limited the length of the primary system line that could be protected. This however perfectly complimented distance protection, which had limitations when the length of the protected line got too short.

The challenge of protecting a transmission line becomes very complex if a three terminal line is considered. Figure 2 highlights one limitation of distance protection when applied to a three terminal line with out-feed effects. This can however be effectively protected by pilot protections suitable for 3 terminal networks. Such a protection would involve communication across all the three terminals.[2][3]

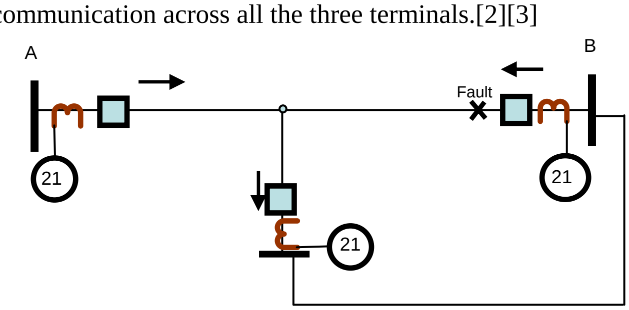

Fig. 2. Three terminal line protection using Distance relay

Figure 3 highlights a differential protection as applied to a line with as many as five terminals. In such applications, it is possible to selectively trip all the breakers only for internal fault without any worry about out-feed effects. The primary requirement is to have a communication link across various terminals. The experience gained in applying pilot wire protection to three terminal networks was successfully extended to longer lines with the introduction of suitable analog to digital conversion at each end and providing a suitable digital link, especially fiber optic cable.

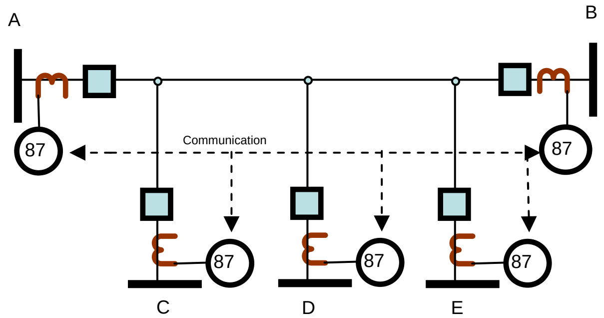

Fig. 3. Typical five terminal line using differential protection principle

B. *Transformer Tap-off in a transmission line*

It has been a challenge to introduce of transformers in such a protected zone of protection. This is because, with only the fundamental phasor information from the other end, it gets difficult to account for transformer in-rush or higher magnetizing currents during over voltage conditions in the absence of information on harmonics.

Figure 4 shows an application of a line system involving tap off for transformers along the line, typically for a major industrial plant. Very often the setting sensitivity or the operating speed of the primary line protection is compromised. The differential protection pickup is typically set higher than the load outflow at the minimum and time delayed sometimes to take care of fault current flow for a through fault in the LV side of the transformer. Most often the transformer is designed with Delta HV winding, providing zero sequence isolation for through ground faults. This results in ensuring good sensitivity and speed for line side ground fault currents. The compromise is typically more expensive insulation of Delta winding than a Wye winding at such voltage levels.

The latest protection systems allow multiple taps along with full compensation for load and through fault current drawn by the transformer taps by measuring the currents on the LV sides of the transformer and communicating with the other ends. The transformer vector group is compensated in the protection algorithm and hence a cost effective transformer can be specified. An added advantage is that smaller generating plants such as wind based power generating plants can be hooked onto an existing power line through a step-up transformer along the way with minimum modification of the primary system. (Figure 5)

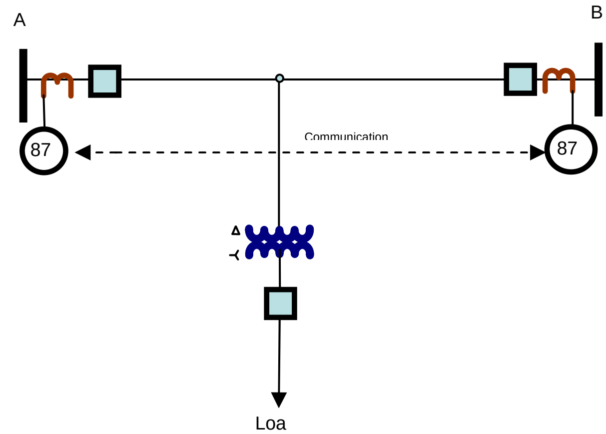

Fig. 4. Protection of a line with tap off Delta/Wye transformer

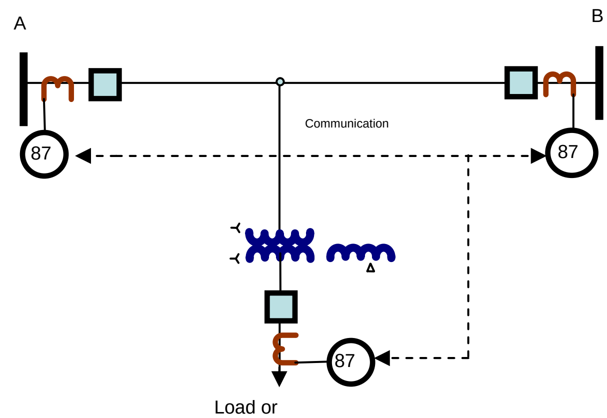

Fig. 5. Protection of a tap off transformer along a transmission line with any vector group with current compensation taken from LV side

C. *Bus protection and the Current Transformer design*

Figure 6 shows a typical EHV substation bus, protected by high impedance protection. The main advantage is the simplicity of protection scheme in that the individual feeders CTs are wired in parallel in the yard and then connected to the protection relay in the control room. One important pre-requisite for this arrangement is that each protected circuit has identical CT ratio with Class ‘C’ CTs of significant knee point voltage and a very low magnetizing current. This may not be a major concern with newly designed outdoor substation.

The above scheme, however, cannot possibly be provided in switchyards as retrofit, where high impedance protection was not planned in the design stage. One costly option is to change all the CTs with an additional core for bus protection. Even discounting the cost aspects, there have been cases when additional cores for bus protection are not possible with tightly placed CT cores. Typical cases are Gas Insulated switchgears and MV switchgears.

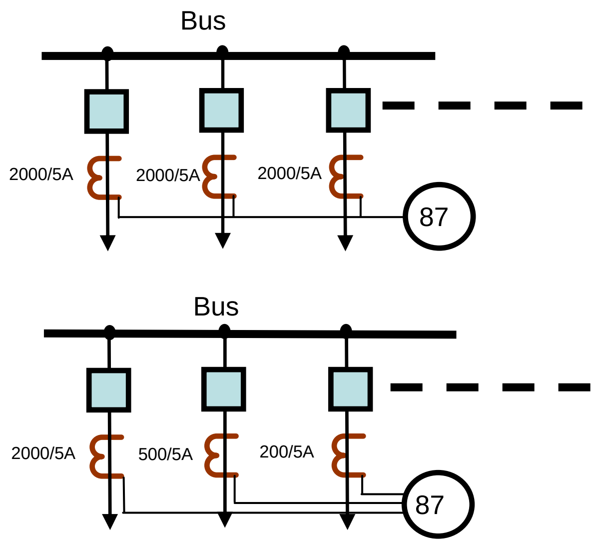

Fig. 6. Bus protection using High Impedance Circulating Current Protection and Low Impedance Protection

In such cases, instead of changing the CTs or the switchgear, the solution today is to use a low impedance bus protection. Numerical protections are available today which read the individual circuit current from each bay. The additional cost is of course the CT lead from each bay as well as individual analog input and processing capability in the IED. The upside is that the above cost is negligible compared to changing out the primary equipment. Additional benefits are fault recording of current waveforms from each bay, sequence of events, communication capability etc. The CT requirements are so low that the protection can very often be connected to one of the existing protection cores serving individual bay protections.

Figure 7 highlights another interesting aspect about the low impedance numerical protection, where, even with double bus with double disconnectors and single breaker primary systems, there is no CT switching involved. This is because the internal processing within the IED routes the current signals to the appropriate protection zone measuring element. The disconnector positions are fed into the IED through binary inputs signals. This is a significant advantage when a typical outdoor breaker-and-a-half scheme is compared against a GIS double breaker arrangement with respect to life cycle costs. The latter is often cost competitive against the former, with significant advantages over its life time including minimum maintenance. The physical ‘non-switching’ of CT currents in the latest bus protections is one significant factor which often clinches the option in favor of double bus GIS arrangement in quite a few countries.

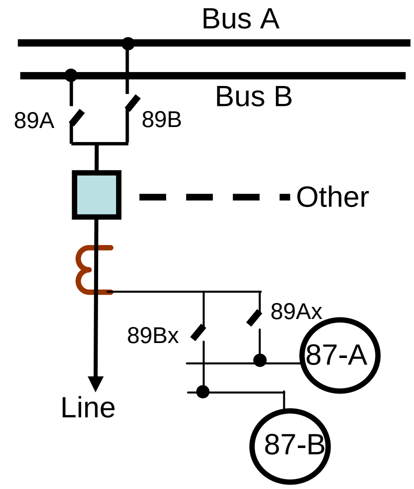

Fig. 7. Double Bus Scheme- CT Switching in a conventional Bus protection

D. Transformer protection and primary system

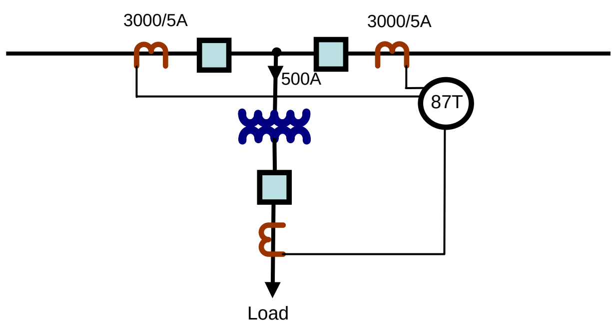

Fig. 8. Transformer Protection involving dual breakers on HV side

When protecting transformers connected to a breaker-and-a-half or a ring-bus system, the CT ratio is decided by the breaker load current rather than the load drawn by the transformer. In the example shown in Figure 8, the breaker CTs are chosen at 3000/5A compared to a load current of hardly 500A through the transformer. Individual CT currents are provided as bias inputs to the differential relay. While stability of through faults across the two breakers is assured with this arrangement, the sensitivity of protection for an internal transformer fault is compromised for sure. One solution to avoid the problem is to provide a load matched ratio CT core in the lead to the transformer. The stub so formed is protected by a differential protection.

The latest developments in the numerical protection algorithms have addressed the above problem without calling for any new current transformer. The protection offers conventional bias so long as the fault is through the two breakers. However, for internal faults, the relay internally calculates the transformer current through a numerical summation and provides less bias input corresponding to the current drawn in the transformer bay.

E. Transformer Feeder design

Figure 9 identifies another area wherein, new algorithms and protections in an IED have altered the way that a transformer feeder is designed.

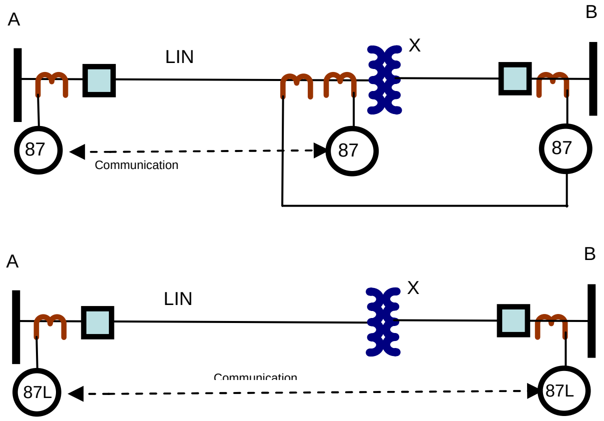

Fig. 9. Transformer feeder protection – Conventional and Modern schemes

The top picture provides an indication of the way a long feeder with a transformer at the end is protected. Bus A is the HV source side and bus B represents the load. In view of limitations of providing a single protection device to cater to both line and a transformer, very often CT is provided on the HV side of the transformer. This is connected to line protection on one side and transformer protection on the other. The line protection is typically a pilot wire based differential protection or a distance protection with communication features. The issue is that the intelligence that would be obtained by analyzing waveforms of the transformer directly as to in-rush or over-excitation condition etc. cannot be done with only fundamental phasor information.

Today with better communication bandwidths and higher processing capability, the latest numerical relays offer the possibility to send instantaneous sampled values to be exchanged across the terminals using digital communication means. With this the remote end information is available in a transparent way, enabling decision making as to whether it is internal or external. Thus including transformers in the zone of protection is no longer a concern while designing primary power systems. This is especially useful in case of a medium length lines feeding a load substation, which may now be terminated directly onto transformers with LV side breakers, avoiding the cost of HV breakers or CTs totally. This results not only saving in HV equipment cost but also other maintenance issues associated with HV sub-station at the receiving end.

F. Breaker-and-a-half scheme CT locations-Tee Zone

Similar to the transformer protection mentioned above, it has been a challenge to protect a line fed from two breaker system such as from a breaker-and-a-half or ring bus. The currents from the two CTs are summed either by external connection or by an internal electronic or numerical means before the signals are fed to the line protection device which could be either a distance or differential element (Figure 10)

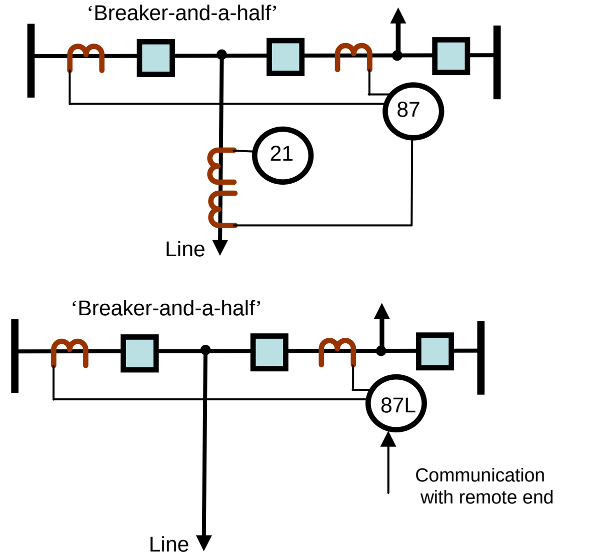

Fig. 10. Line Protection involving dual breakers- Conventional and modern schemes

The differential protection has the same issues as discussed for transformer protection as above whenever the line load current and fault currents are low compared to the CT ratio.

With respect to line distance protection the assumption has always been that the CTs would be sized not to saturate. However, there have been instances, for a through fault across the two breakers, one of the CTs saturated because of residual magnetisms. The relay is fed with a summation of two CTs which no longer represents the actual system conditions. This may lead to mis-operation.

One good solution is of course to provide a dedicated CT in the protected line for taking care of the line protection and take care of the stub formed with a differential protection. The latest numerical protection technology addresses the above issue in two ways. With respect to differential protection solution, it is possible to provide individual current bias inputs to the relay. Saturation detectors are provided to detect any significant current transformer saturation and act accordingly to take care of through faults across the breakers. With respect to line distance protection, it is possible to provide directional detection in each breaker and validate tripping only for line faults. Either way, the need for a separate CT and associated protections are thus avoided.

G. Wide Area Measurements and Controls and its impact on primary power system loading

Thanks to GPS systems, the time stamping of IEDs has gone to accuracies of the order of microseconds. In other words, it is possible to accurately determine the phase angle of voltage and current phasors to a level of accuracy which was not possible earlier. Since the phase angle difference across a transmission line directly signifies the power transfer across the line, it is possible to send power across the line to a level closer to theoretical maximum limits. Conversely, the transmission system can be designed close to the amount of power that needs to be transmitted without any major design margins. [4]

H. IEC61850- Impact on primary system design

Another important progress that has been made in the field of protection, communication and control of a substation IED is the standardization of the ways the IEDs communicate and present themselves to the other IEDs and other intelligent systems in the substation. The international standard IEC61850 addresses the above in detail [5]. Interoperability of IEDs in the sub-station is one significant goal of the above standard. It is possible to exchange data including measured current information between various IEDs. The following method suggests how the various bus section currents can be measured once the individual breaker currents are measured.

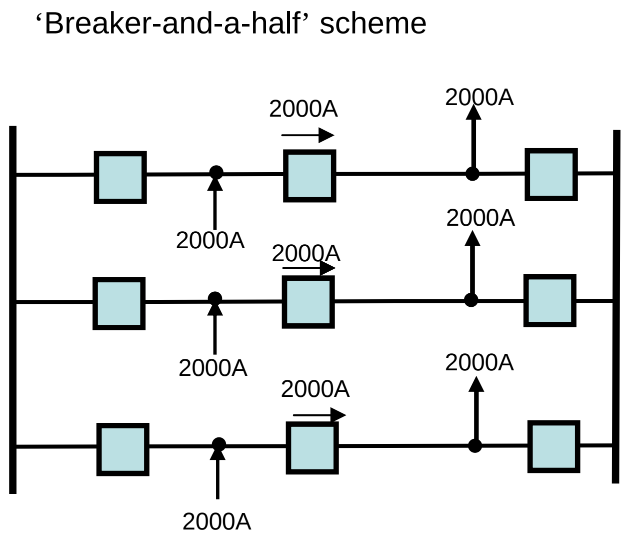

Fig. 11. Typical currents flow in a Breaker-and-a-half scheme

In Figure 11, the currents in the breakers are directly measured using CTs on each breaker and thus the currents in the bus section can be estimated to be zero. In another situation with two section breakers open (Figure 12), the currents in the bus-sections would shoot up, which can again be estimated using IEDs which are measuring the breaker currents. The interchange of analog signals and breaker status between each IED helps to see if the bus sections are getting overloaded. This aspect could be taken into account while designing the bus thermal ratings, without fear of overloading of bus sections during extreme operating situations.

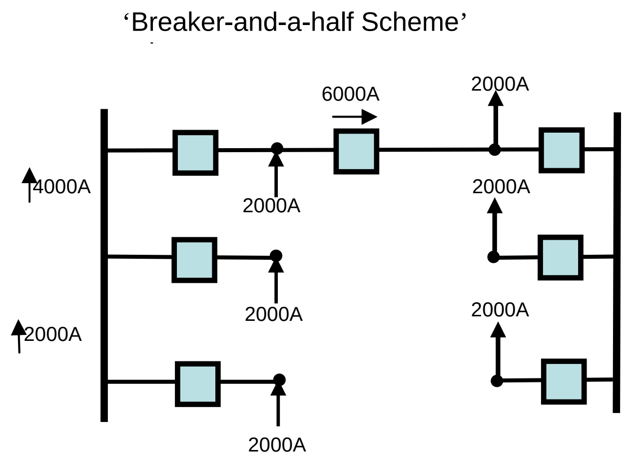

Fig. 12. Typical currents flow in a Breaker-and-a-half scheme with a few breakers opened out.

I. *Remote End Reclosing Supervision*

Another challenge of protecting a transmission line is not involved with the fault clearing, but rather the restoration of service after the breakers have opened. How the line is restored can have a significant impact on the stress the circuit breakers are subjected to and consequently, the short term maintenance interval, and log term life for the circuit breakers. Figure 13 illustrates a line protected by a current differential relay. These current differential relays are equipped with autoreclosers for each breaker. In addition, the current differential communications channel also allows for binary information to be transferred from one relay to the other.

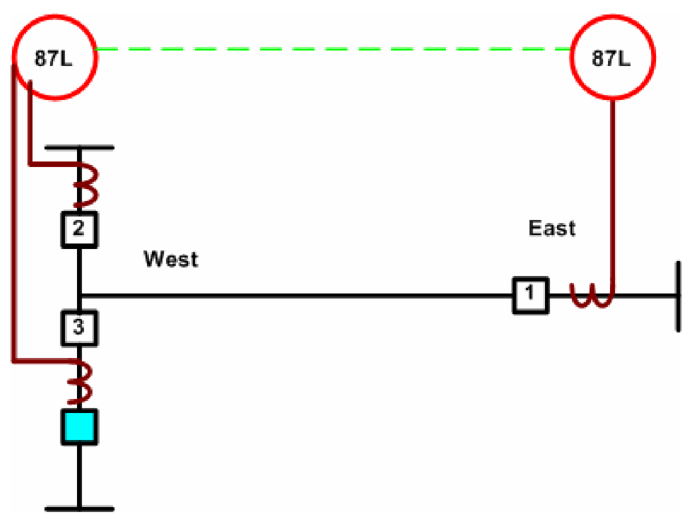

Fig. 13. Line Reclosing Example

The system connected to the East substation is much weaker than the system connected to the West substation. All three breakers 1, 2, and 3 are open. To put the least amount of stress on the system, breaker 1 at the East substation is closed first on Hot Bus, Dead Line. If breaker 1 recloses successfully, the relay sends a SUCCESSFUL RECLOSE to the remote end. Upon receiving the SUCCESSFUL RECLOSE from the remote end, the inhibit is removed from breaker 2 autorecloser, and it recloses, via synch check after a time delay. If breaker 2 recloses successfully, then after a further time delay, breaker 3 closes. Since the autorecloser functions for breakers 2 and 3 are in the same relay, each autorecloser knows the status of the other breaker. E.g. whether the breaker is in service, is in alarm, or out for maintenance, and can take over reclosing accordingly. Since they know breaker 1 has successfully reclosed, they are not subject to the stress of closing into a fault with a strong source behind them. The result is an extended Breaker life.

II. Conclusion

Progress in protection, automation and control technologies continue altering the way primary power system apparatus are specified, engineered and installed. The new developments provide better methods to use existing equipment and help significantly reduce the cost of new installations as well as operate the system in a more efficient manner. It is thus suggested that perspectives on substation design should always consider the rapid developments that are happening in modern IEDs.

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III. Biographies

Roger Hedding is the Regional Technical Manager for the Substation Automation and Protection Division of ABB in Milwaukee, Wisconsin. He received his BSEE from Marquette University in 1971. From 1971 to 1988, he worked for Westinghouse Electric Corporation in several engineering positions, joining the Graduate Student Training Program. He was a Transmission Engineer in the Transmission and Distribution Engineering Department of the Power Systems Company in Pittsburgh, PA. In 1988 he became part of ABB in the transition from Westinghouse. In his current position as a Regional Technical Manager for the Central Region he is responsible for the application, and technical issues associated with ABB relaying products. He has authored and co-authored several technical papers in the area of protection. He is a senior member of IEEE, a member of IEEE Power Systems Relaying Committee, and a registered professional engineer in the state of Wisconsin. His areas of interest include protective relaying applications.

Sethuraman Ganesan received his BE (Honors) degree in 1982 from College of Engineering, Guindy, University of Madras, India. He started his career in Tata Consulting Engineers, Bangalore, specializing in electrical design of major power plants. From 1985, he worked in power system protection application and design in Areva T&D (English Electric), Chennai, ABB in Saudi Arabia and in Deprocon. In 2001 he joined ABB in Allentown, PA as senior application engineer and product manager in the area of transmission line protection. In 2006 Ganesan moved to ABB, Bangalore and presently he heads the Business Development section in their Southern regional marketing office. He is a member of the executive committee of PES, Bangalore Chapter of IEEE. His areas of interest include power systems, protective relaying algorithms, applications and testing.

Back to the Table of Contents