INTEGRATION OF FAULT CURRENT LIMITERS IN CASE OF GENERATION CAPACITY ADDITION AT A CEMENT PLANT - A CASE STUDY

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SYNOPSIS

Energy management needs of a plant being upgraded in capacity often requires captive power generation / augmentation. This puts into focus the need to review the fault levels of the system and ensure withstand capabilities of all the electrical components. A serious situation develops if the fault levels are increasing beyond the system ratings, and the solution may demand replacement of large number of electrical switchgear equipments which is a very costly proposition. Alternately one can introduce elements such as reactors in the circuit that will reduce the fault currents but these have their own issues in terms of voltage regulation and losses. This paper addresses the applicability of electronically controlled fault current limiters in the context of a case study involving generation capacity addition at a cement plant.

1. INTRODUCTION TO FAULT CURRENT LIMITERS

In order to understand Fault Current Limiters, a good place to start is with a problem statement. This may best be expressed by relating experiences that you may commonly encounter. Do you ever run into these conditions?

A. Upgrade of a Service Entrance or Substation pushes the available fault currents beyond your system limits. What are the options to replacing all of the underrated switchgear?
B. One could avoid a service entrance upgrade and improve system regulation if you could simply Close the Tie Breakers (now open due to excessive fault current).
C. A Cogenerator Addition yields fault contributions beyond system limits. Replacement of all the impacted gear or reactor regulating voltage makes the cogenerator addition far less attractive.
D. The regulating voltage across a Current-Limiting Reactor prevents startup of a large new motor, or its startup causes a voltage sag that disrupts other equipment on the system. Also, what about the continual losses ?
E. Energy Limitation is required to prevent catastrophic tank rupture of a failed transformer or other equipment. While current-limiting fuses are commonly applied on lower rated units, how about the larger transformers?

What if these typical problems did not exist as a major barrier for system engineers? Solutions of all are in the domain of G&W's CLiP® Current Limiting Protector and PAF® Power Assisted Fuse. These will be referred to hereinafter as Commutating Current Limiters (CCL), sometimes called Triggered Current Limiters. They fill a unique over-current protection role in the higher continuous current range of medium voltage (1-38kV) equipment where traditional, meltable element fuses generally do not exist. Most of this discussion will be oriented toward the CLiP.

2. TYPICAL SOLUTIONS

What are the more common options? What are the typical benefits and drawbacks of each? It should be noted that there is a role for each, and that any one may be the best solution for a particular system configuration and user need.

1. Replace or upgrade all of the circuit breakers and upgrade system bracing throughout. This is often the most expensive solution. It meets the overall goals. If the speed of interruption is not improved, however, it will not limit the greater fault energy level which is related to the square of the current.
2. Open the tie between multiple sources. This may work well with double-ended substations as applied by many plants. It is a simple and effective solution but often undesirably affects system regulation. If the system is not well balanced, one of the transformers may be overloaded. If a cogenerator is added on one bus, its benefits can not be transferred to the adjacent bus without closure of the tie.
3. Apply current limiting reactors to limit the fault. This permits usage of the existing equipment and will reduce the fault energy. It results in a continual operating energy loss due to the resistance (not reactance) of the reactor. This is often neglected and for larger reactor banks may be quite significant. It imposes a regulating voltage drop on the system which often prevents startup of larger motors. It may also impose an unwanted phase shift to the system or impede the supply of VARs from a cogenerator.
4. Apply a Commutating Current Limiter. This will limit faults within the momentary and interrupt fault duty on the existing equipment. It will also permit the equipment to interrupt lower level faults, within its capabilities, without operating a Limiter. If it operates, however, the Limiter's interrupter must be replaced. This is the least well recognized option presented. The Commutating Current Limiter will be explored in greater detail below.

3. CCL CAPABILITIES

Lets explore the most common questions. Why do these devices exist? Why will traditional meltable-element fuses not work? What capabilities for system voltage, continuous current and maximum interrupt are available?

These products were developed in the late 1970's as part of an EPRI-funded project. They cover a need where meltable fuses reach their practical limit. For example, at 15.5kV, the meltable element fuses are generally available to 200A continuous (but are already in a double-barrel design) with some manufacturers reaching up to 300A continuous (in four-barrel designs). For these traditional fuses heat rejection becomes a major consideration. Also, the very high let-thru current may be in excess of the crests of many systems. In other words, it may not limit current to a usable range if it limits peaks at all for the corresponding available current.

The Commutating Current Limiters cover a continuous current range from 200A to 5000A. Available voltages are from 2.8kV to 38kV. Higher voltages are projected for the future. Interrupt ratings are 40kA rms, symmetrical for all ratings with most having an optional 120kA rms, symmetrical interrupt rating. While not common, there are a surprising number of applications of what seem to be unbelievable available fault currents of 65, 80, 95 and even 115kA rms, symmetrical. These devices have literally interrupted 311kA rms, symmetrical at 15.7kV. The formidable current-limiting capability at extreme fault levels adds a whole realm of possibilities to the overcurrent protection spectrum. Energy rejection is minimal with a 15.5kV, 3000A unit rejecting approximately 140 watts per phase.

Another factor to consider with a CLiP® type of Commutating Current Limiter is that the continuous current is, for all practical purposes, completely independent of the current-limiting performance of the device. These are electronically sensed and triggered units whose operating criteria is preset and not dependent on time versus temperature, element size (or melting I^2t) or preconditions. They are catastrophic protection devices that allow circuit breakers and other lower rated devices to clear faults within their capabilities. The Commutating Current Limiters described in this paper are intended to operate at more severe overcurrent levels, typically beyond the limits of the existing equipment.

4. CCL USERS

Users come in many forms. Utilities account for approximately 25% of the users, primarily applying the limiters as a substation or generating station device. They have been used in the protection scheme of nuclear plants. Government bases and research facilities account for approximately 7%. Universities, office complexes and medical centers account for about 8%. The mainstay of the users, say 60%, are in the industrial sector.

CCLs are presently applied on 5 continents and on oil well processing ships offshore. These devices may be placed indoors or out, from -40 °C to +40 °C and beyond. They do not require enclosures for use outdoors and are often suspended from steelwork or crossarms. Units are commonly enclosed in switchgear lineups and have been adapted to busduct arrangements. They have also been adapted to circuit breaker trucks for simple insertion/removal.

In the industrial sector the users vary widely from pulp & paper, petroleum and chemical processors to automotive plants, steel mills and gold mines. They provide protection to the reportedly 1st and 2nd largest steel mills in the world (in Korea and Brazil), the world's largest paper pulp facility (in Brazil), newsprint mill (Canada) and highest volume wellhead in the southern hemisphere (Indian Ocean). They are applied to protect cogenerators on test by their manufacturer as well as at installations in the field. Lets look more specifically at how they are applied to resolve those issues listed in the problem statement.

5. APPLICATION AND PERFORMANCE

The general philosophy of these Commutating Current Limiters is to act as catastrophic protection for the system. In other words, let the overloads and lower level faults be cleared by downstream devices operating within their capabilities. Clear the major faults with the Limiter.

Lets first look at the system limits. We will have set the limiter so that the equipment will not be overexposed from interrupt or long term thermal standpoints. How do we determine whether or not we will exceed the short term or momentary conditions?

If you originally have breakers rated for 20kA rms, symmetrical interrupt at 5 cycles (I will avoid k-factors etc. in this work), the downstream breakers will typically be able to handle 2.7 times this amount as a peak, asymmetrical value on the first 1/2 cycle. Remember that the instantaneous peak of a 20kA rms, symmetrical wave will be $\sqrt{2}$ (or 1.414) times that value giving 28.28kA inst. When fully asymmetrical or offset (due to a fault initiation on that phase of zero degrees on the voltage wave), the crest can theoretically be double that magnitude ($2 \times \sqrt{2}$) or 2.828 times that number for an infinite circuit X/R. From a practical standpoint it is uncommon to find general substation circuit X/R values greater than 30 which would yield a multiplier of 2.69 for that system. For generator circuits, where it is not uncommon for the circuit X/R to be 75 or higher, this value approaches 2.8. [As a side note, CCLs perform very well interrupting the very high X/R circuits since they introduce a high resistance to the circuit during the interrupt process which is discussed later.] This leads to the fact that the peak asymmetrical crest that the circuit breaker is capable of is typically in excess of 2.7 times the rms symmetrical interrupt rating during the first peak. A maximum of 2.5 times the rms symmetrical rating is typically applied as a limit (which is in agreement with certain standards). The actual value should be verified by the circuit breaker manufacturer.

One does not want to exceed this value as the electro-mechanical forces resultant from the square of the current may fracture insulating supports, bend bus, disengage contacts or cause "popping" at the contact surfaces due to the repelling forces overcoming the contact spring force. Since most equipment on the system will have a one second or three second rating equalling the rms symmetrical interrupt rating of the breaker, there should be plenty of thermal capability if we stay within its instantaneous peak capability. In other words, the thermal limits are generally not an issue since the fault duration will only be a fraction of a cycle.

Let's consider the first problem, Upgrade of the Service Entrance or Substation in Example 1. We will assume a dual transformer supply. We will also assume that the original transformers are replaced by ones which yield an available fault current of 15kA for a total of 30kA rms symmetrical versus the 20kA rms symmetrical rating of all downstream equipment.

The first plot depicts the interruption of one transformer under fully asymmetrical conditions. The operating point had been selected as 14kA instantaneous amperes. We will not explore the methodology of trigger level selection as that is a very lengthy topic, but instead, will provide appropriate selections. The point of peak let-thru (after triggering, commutation and shunt fuse melt of the limiter) is 17.5kA instantaneous. The available current is the full dashed outline. The shaded area is the projected current through the Limiter. The point of peak let-thru is well before the point of current extinction. This characteristic is described in greater detail in the operating sequence. A symmetrical wave would have reached its point of limitation at a much earlier time and final extinction would have occurred at 1/4 cycle. The fully asymmetrical fault will be depicted throughout the examples as this is typically the worst case for momentary duty as well as energy let-thru.

The removal of the one transformer source will keep the circuit breakers within their interrupting range. One can show that the instantaneous (momentary) current capabilities of the gear will also not be exceeded. This can be accomplished by a more traditional means of using let-thru curves and adding to the other sources but with an accommodation for the timing of the peaks. An improved method, by computer generation, is depicted in the second plot for the tie closure problem.

In Example 2 we depict the Closure of a Tie within the system. We have also added a cogenerator as this is increasingly common. Lets assume that a fault occurs at the location shown. We have 16kA rms symmetrical available thru the limiter for a total of 25 but with the equipment limit at 20. Available currents on both sides of the tie are shown on the plot as well as the total to the fault.

The Limiter's current profile is depicted by the shaded area. If we add the instantaneous current of this shaded area to the "residual current" from the faulted side of the tie (which does not flow through the Limiter), we can project the total instantaneous currents to the fault with reasonable accuracy. You will note that the peak does not occur at the time of peak fuse let-thru in this example. Also, it is not equivalent to the peak let-thru of the Limiter added to the crest of the "residual current" wave. In some other cases the peak let-thru condition will occur at the peak let-thru point of the Limiter. These conditions are more difficult to project with traditional meltable element fuses. With the aid of a computer these plots are readily generated for virtually all users of the CLiP® Commutating Current Limiter. It permits them to visualize what is occurring without much guesswork.

Following CCL clearing, the buses are separated and the downstream breaker can safely interrupt the "residual fault," which is still supplied by the left source transformer. While load shedding may be necessary as a temporary measure to sustain the left bus, critical processes or operations will usually not be dropped. Not shown on the Example 2 circuit diagram is a disconnect switch to the left side of the Limiter. Opening this and the tie breaker will enable replacement of the expended Limiter without de-energizing either bus.

The Addition of a Cogenerator has been depicted in Example 2 as well. In many cases the system engineer will decide to place the Limiter in the cogenerator supply bus instead of at the tie. This will (for Example 2) permit the breakers and other equipment to operate within their ratings while providing exceptional protection to the generator itself. Should a fault in a generator winding occur, the fault energy as supplied by the utility transformers is greatly reduced. Let-thru I^2t values (approximately proportional to fault energy) are typically one-half % of that through a five cycle breaker. A winding meltdown may be reduced to little more than a puncture. Given the value of the cogenerator unit, it is excellent insurance. From an operating perspective, the triggering and let-thru characteristics are similar to the tie-position application.

If we consider the reactor, this certainly has a solid place in the protection world. A few drawbacks were previously listed. These can, however, be mitigated by Bypassing the Reactor with a Commutating Current Limiter. The secret here is that this combination maintains the benefits of the reactor without the operational drawbacks. It is a more costly scheme than some of the others but can avoid the operation shutdown since the sources are only limited and not interrupted. Very simply, the Limiter carries virtually all of the continuous current. Therefore the continual losses and regulating voltage imposed by the reactor are avoided.

If a fault should occur in Example 3, the Limiter operates and thereby commutates the reactor into the fault circuit. This in-turn limits the magnitudes within the ratings of the downstream equipment. The lessened fault level is then cleared by that downstream equipment. After the fault is cleared, the reactor continues to conduct load current to the system such that the critical processes are not shut down or otherwise compromised. Power is not lost to the critical loads as would happen with the Limiter itself. The bypass switches are then opened to isolate the Limiter and change the expended interrupter. Following replacement, the bypass switches are closed to re-bypass the reactor.

The Plot 3 projection is an approximation. The Limiter will commutate the fault into the reactor well before the system's voltage zero point due to the reactor voltage which will be far less than system voltage. The actual time is highly dependent on reactor characteristics, distance from the Limiter, cable/bus runs etc. A typical range is 0.5 to 1.0 millisecond. Reactor bypass accounts for approximately 25% of the Limiter applications.

The last problem suggested at the start of this paper is Energy Limitation. This was discussed in the cogeneration analysis above. Since the Commutating Current Limiters are so effective at limiting energy, we enter a realm where we begin to look at the possibilities of keeping the lids on faulted transformers. The circuit breakers may be capable of interrupting the circuit but not necessarily in time to prevent the catastrophic tank rupture. This applies to catastrophic failure of other equipment as well. Particularly for the transformer, the sensing of the fault is often difficult. The first indication may not come from current sensing relays, but from instantaneous overpressure or change of pressure relays. Protection becomes feasible from the standpoint of remote triggering of the Limiter in response to these other inputs such that the fault is cleared at an early stage. Discussion of how this is performed at such speed follows.

6. CCL OPERATION

The essence of the operating procedure will be given below. It will not go in technical depth but rather into an overview, seeking a generalized understanding of the process.

These devices can be characterized by a primary conduction path which electrically parallels a special current limiting fuse of very high energy absorption capability and low melting I^2t. Upon incident of a fault meeting the triggering criteria, the primary current path is opened - essentially a high-speed switching operation. This causes commutation of the fault current into the current-limiting fuse and its rapid interruption. The interrupt process of this fuse is typical of the traditional current-limiting fuse with 1/4 cycle interruption of symmetrical and 1/2 cycle interruption of asymmetrical faults.

1. The Normal Operating Condition - The primary current path is a busbar with precision-machined notches. This forms the basis of the high-speed switching portion of the unit. The current limiting fuse, being a higher impedance path, carries a minuscule portion of this continuous current.
2. Triggering Logic Senses a Fault and Responds - As the fault is initiated the current begins to rise. At the point where the fault conditions meet the operating criteria, the triggering process begins. These units use a threshold-level sensing system, not a rate-of-rise sensing system. The current must actually reach a preset level and be held for 80 microseconds. The intention is to refrain from triggering in response to transients and harmonics where the rate-of-rise of the current may be quite high, but a fault does not exist. Also, the maximum rate-of-rise of an asymmetrical fault will occur half way to its crest. We will generally want to have operated and

be in the clearing mode before that time. With the threshold level sensing system, these units are not limited to bus and line-up protection. These CCLs are also effectively applied in capacitor bank and harmonic filter switch protection schemes. Upon meeting the triggering criteria the triggering logic sends a pulse the actuator.

3. The Actuator is Initiated - This begins the interrupt process. The actuator in-turn operates a high-speed cutting charge which literally cuts through the notched section of busbar. This is the basis of the high-speed switching process. Note that while the drawings indicate a single switch, there are actually a multiplicity of cuts in the bus. For example, there are four cuts or switching points in the 15.5kV bus. The switch opening time following the cutting process is approximately 13 microseconds. The tube surrounding the bus remains in tact, capturing the ionized gases. No blast of these gases occurs outside of the tube.
4. The Switch Opens, Fuse is Commutated into Circuit - The actuator opens the high-speed switch which draws an arc and yields the corresponding arc voltage. This is multiplied by the number of cuts. The effective commutating voltage is accordingly higher for multiple cuts than with a single cut. This provides for a more rapid commutation of the fault current to the shunt fuse and improved dielectric withstand. As commutation is completed, the current-limiting fuse carries the full magnitude of fault current and is in the melting process.
5. The Fuse Melts and Interrupts - While the fuse is in the melting process the high-speed switch must recover dielectrically so that it will withstand the arc voltage of the current-limiting fuse. With the low arc times at the switch and therefore a low ionization level, the dielectric recovery of the switch is very rapid, in as little as 50 microseconds.

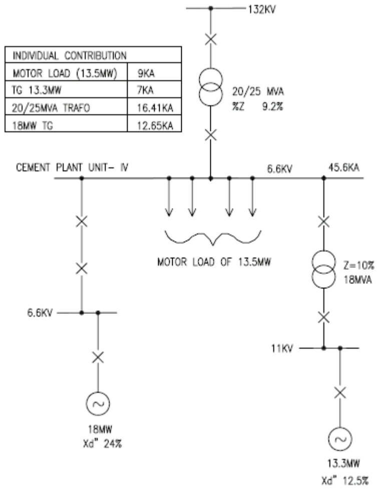
   Upon completion of the melting process, the arcing of the fuse begins. The arc voltage caused by the inductively driven current through the resistance of the fuse yields an instantaneous fuse voltage greater than the system voltage. This is responsible for the rapid reduction of fault current. Interruption is not instantaneous however. Though the current falls quickly it will not be fully extinguished until nearly at the voltage-zero point.

   Note that this is not the current-zero, the point of interruption for circuit breakers, expulsion type fuses and other interrupters. The fuse is absorbing much energy in melting the element and the surrounding quartz sand interrupt media. This is a high resistance that is now being introduced into what is typically a highly reactive fault circuit. Consider that the current and voltage may initially be as much as 90 electrical degrees out of phase. During the interrupt process a phase shift occurs which brings the current and voltage back in phase with each other. This yields an ultimate clearing at the zero point for both. It occurs at 1/4 cycle for the symmetrical fault and 1/2 cycle for the fully asymmetrical fault (with varying asymmetries in between). The characteristics of the current-limiting fuse in this paragraph are typical of any current-limiting fuse clearing a heavy fault.
6. The fault has been cleared - The fuse quickly cools and recovers into a non-conducting mode. The fault has been cleared.

Conceptually, in simple terms, the device contains a high-speed switch that carries the continuous current. Upon sensing of a fault by the electronic triggering logic, the switch is opened and the current is forced into a current-limiting fuse that interrupts the circuit. In this way the Commutating Current Limiter provides an effective means of protection without costly equipment replacements or introducing unwanted performance characteristics to the system.

7. CASE STUDY – CEMENT PLANT

This case study is regarding an application requirement of a Current Limiting Device which can limit the short circuit current from 45.6 KA rms value to 37 KA rms value on a 6.6 KV bus. The plant has an existing 18 MW generator and motor load of 13.5MW connected on a 6.6KV bus. Addition of a 13.3 MW generator on the same bus makes the short circuit contribution on the bus around 45.6KA thus violating its current fault levels of 40 kA.



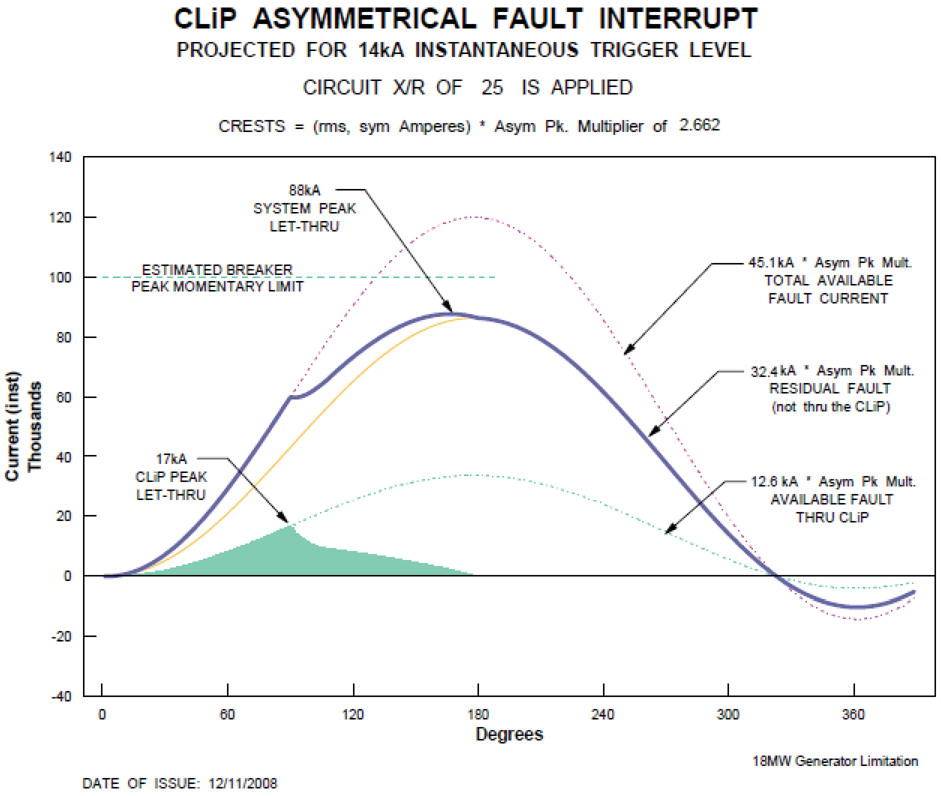
The short circuit limiting device is proposed to be introduced in series of 18 MW Generator so that the major fault current contribution of 18 MW TG set (12.65KA RMS) can be avoided on 6.6KV bus. Refer the Single Line Diagram of the plant (SLD).

The proposed solution to comprehensively address this requirement is as follows:-

Three (3) phase type "CLiP®" Current Limiting Protector rated:
15.5 kV, 1200 Amp Continuous Current,
110 kV BIL 40 kA rms, sym. Interrupt,
14 kA maximum instantaneous trigger level range

The following points are noteworthy:-

1. There is no need to have complicated directionality based features which can make the system unreliable.
2. The scheme prevents triggering on a 132kV system fault, since the peak asymmetrical portion of the fault current from the generator, with all sources contributing, will be less than the trigger level, so an operation for a 132kV system fault would be blocked. If the 13.3MW turbogenerator is disabled, an option is provided to disable the CLiP.
3. Motor Starting Inrush: If the transformer and other generator are energized, the inrush will be split between them proportional to their fault current. If they aren't energized, then the CLiP does not need to be activated -- so it can't possibly trigger. Even if all 13.5MW is energized (assuming .85 power factor) and a 6 times multiplier for inrush times another 2.5 multiplier for peak asymmetry, one gets a maximum peak of 20.8kA instantaneous. About 35% of this or 7.3kA peak is from the 18MW generator. This is about 1/2 of the trigger level value. Thus, there is no need to provide directionality since the motor inrush would never trigger the CLiP.



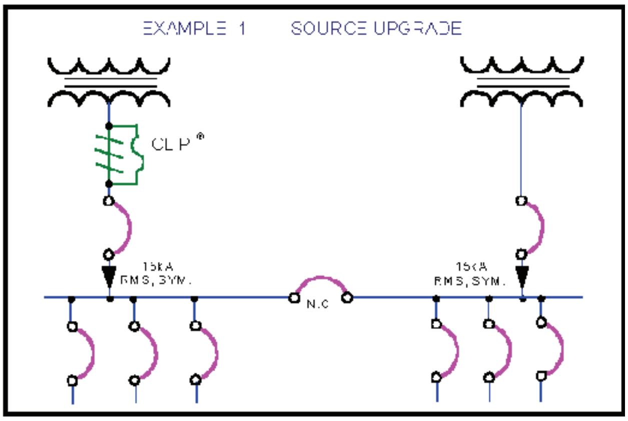
8. BIOGRAPHY

John S. Schaffer, an employee of the G&W Electric company since 1982, is General Manager of the System Protection Division and was previously employed by Allis-Chalmers Corporation. He has BSEE, BSME and MBA degrees and is a registered PE. John is a Senior Member of IEEE and is a member of its High Voltage Fuse Subcommittee, the Pulp & Paper Industry Committee as well as a member of the NEMA High Voltage Fuse Technical Committee and TAPPI. John has authored and co-authored numerous technical papers on fusing and switchgear topics for IEEE, the American Power Conference, CIGRE and CIRED. He is a holder of four U.S. patents and their foreign counterparts.

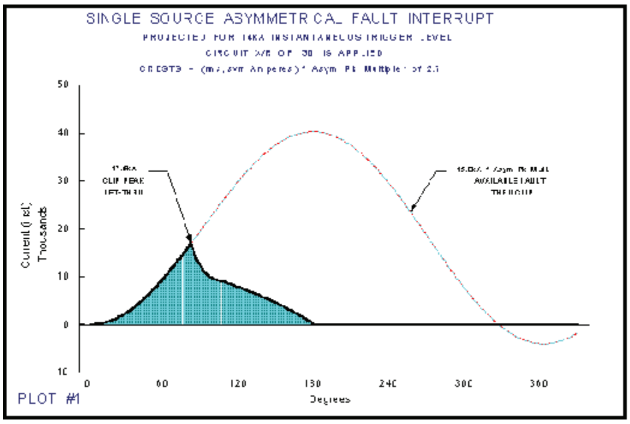
Manish Patel, an employee of the G&W Electric Company since 2004, is Regional Vice President – South Asia and was previously employed by Aplab group. He did his B.E. in Electrical Engineering from Pt. Ravi Shankar University, Raipur (89-92). He did his MBA, C.C.E.M from Indian Institute of Foreign Trade, Delhi. He started his career from the Insulators Industry and through out his 16 years of professional working he has been associated with the Electrical utilities and industries.

Amit Raje did his B.Tech in Electrical Engineering from the Indian Institute of Technology, (Mumbai, Maharashtra, India, ‘91-’95). He then did his M.S. in Electrical Engineering from the University of Minnesota, (Minneapolis, MN, USA, ‘95-’96) in Power Systems. He has worked as a Senior Engineer with Open Systems International, (Plymouth, MN, USA) during ‘96-’97 in the field of Energy Management Systems. Since 1997, he has headed the R&D division of Aartech Solonics (Bhopal, MP, India) and has focused on the research, development, testing, engineering and commissioning of Fast Bus Transfer Systems for the utility and process industries. In April 2007, he succeeded his father, Anil Raje – Original Pioneer of Fast Bus Transfer Systems in India – as Managing Director of the company. He is a professional IEEE member and has authored several international conference technical papers in the past. His other field of work is related to development of tamper proof microprocessor based energy meters, and has filed a patent in this regard. His research interests are focused on the development of innovative, embedded and integrated power system solutions to consumers, utilities and industries. He can be reached at amitraje@aartechsolonics.com or mobile (+91-9993091164).

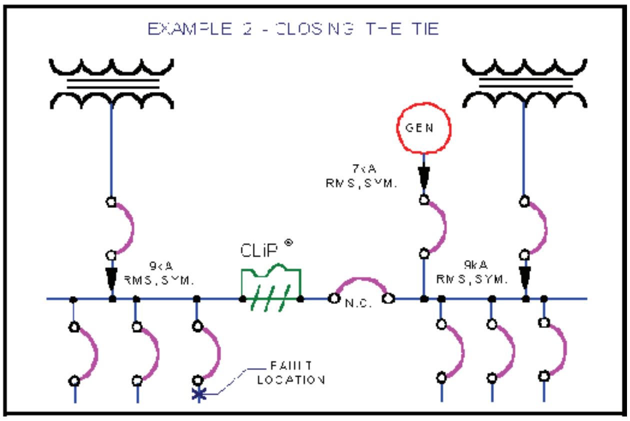
Example 1: Circuit Diagram



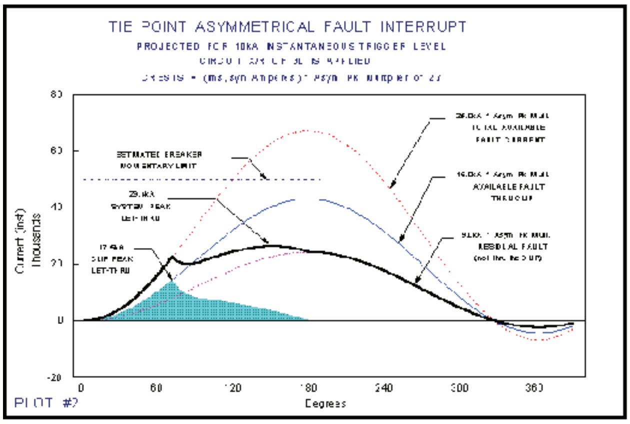
Example 1: Plot



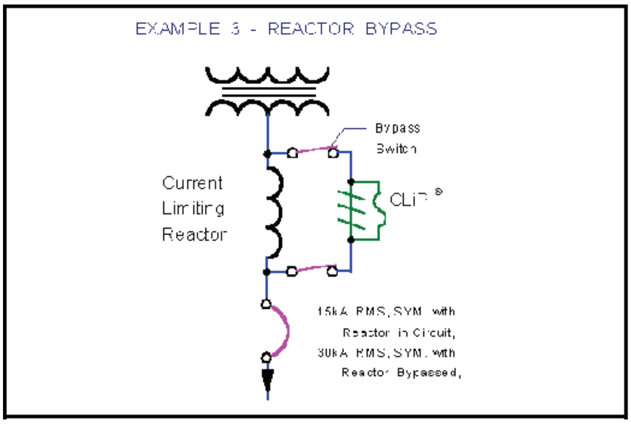
Example 2: Circuit Diagram



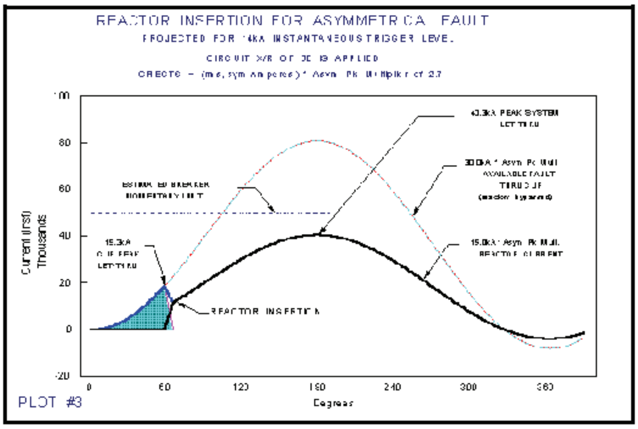
Example 2: Plot



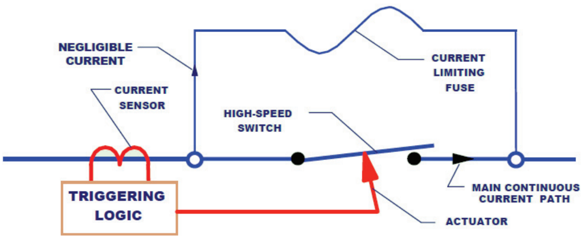
Example 3: Circuit Diagram



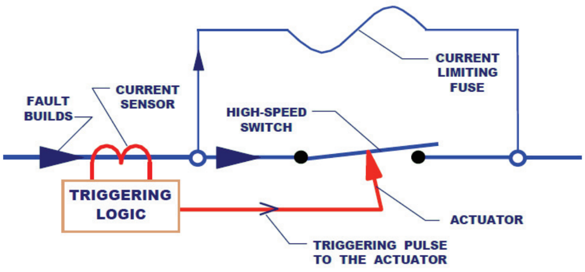
Example 3: Plot



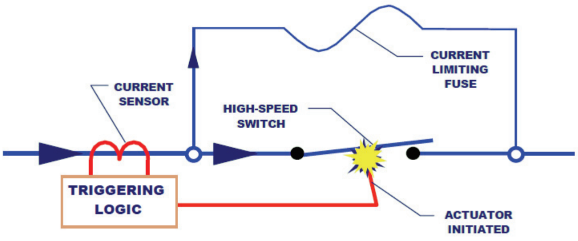
1. NORMAL CONDITION (UNTRIGGERED)



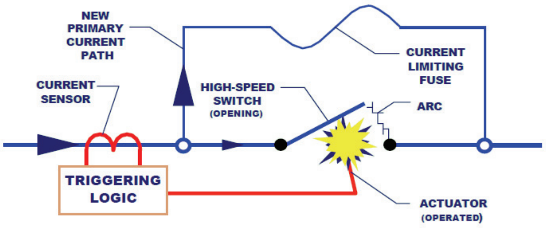
2. TRIGGERING LOGIC SENSES FAULT AND RESPONDS



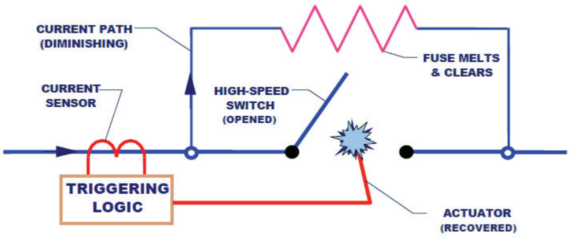
3. ACTUATOR INITIATED



4. SWITCH OPENING – SHUNT FUSE IS COMMUTATED INTO CIRCUIT



5. SHUNT FUSE MELTS AND INTERRUPTS



6. CIRCUIT CLEARED