# TRIGGERED CURRENT LIMITERS FOR CLOSING BUS TIES, BYPASSING REACTORS AND IMPROVING POWER QUALITY

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*Abstract* - **Current limiting fuses have been commonly applied in protective systems for decades. They are effective for controlling peak currents and for limiting fault energy. Triggered Current Limiters (TCL's) are higher continuous current, electronically controlled variants of the more conventional technology. They are applied in the traditional current limiting fuse roles, but in addition, adapt readily to unique applications such as bypassing (shunting) current limiting reactors and closing system ties between adjacent buses.**

**Bypassing reactors with TCL's can eliminate the continual losses and regulating voltage drop associated with current limiting reactors. This application provides full protection during a fault and load continuity following a fault. By closing system ties through a TCL the user may improve switching flexibility, better balance transformer loads, and/or start large motors with less system voltage sag. This paper investigates the practicality, the benefits and the limitations of TCL's in these specialized applications. It also introduces the concept of using TCL's for power quality enhancements on critical circuits where a bus fault may cripple an adjacent unfaulted bus.**

Key Words – Fuses, current limiting, Triggered Current Limiter, TCL, Commutating Current Limiter, CCL, bus tie, reactor, power quality, CLiP®, PAF®, shunting, power quality

## I. INTRODUCTION

Triggered Current Limiters (TCL's), sometimes referred to as Commutating Current Limiters (CCL's), fill a unique overcurrent protection role in the high continuous current range (up to 5000A) of medium voltage (1–38kV) equipment where traditional, meltable-element current limiting fuses reach their practical limit and generally do not exist. 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 4-barrel designs). Heat rejection becomes a major consideration for these traditional fuses. 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. They essentially reach a practical limit in their development and usage.

The traditional means for limiting faults for higher continuous current systems has fallen into a number of approaches:

1. Addition of a current limiting reactor to reduce fault currents within system capabilities,
2. Open a system tie to eliminate some of the sources of fault current,
3. Upgrade the switchgear and other overdutied equipment to higher ratings, beyond the fault spectrum.

### A. *TCL Characteristics*

Coming into general use during the last 2 decades, the TCL's offer a high continuous current alternative to these techniques by providing effective fault current limitation without the significant losses, and without equipment upgrade or replacement. TCL energy rejection is minimal. For example, a 15.5kV, 3000A unit rejects only 140 watts per phase. Two such Triggered Current Limiter units are the CLiP® Current Limiting Protector and the PAF® Power Assisted Fuse. The CLiP utilizes electronic sensing and triggering while the PAF uses an element sensor for initiation of triggering. We will focus on units with electronic sensing in this paper. Interrupt ratings are 40kA rms, symmetrical for all ratings with most having an optional 120kA rms, symmetrical interrupt rating. These devices have interrupted up to 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. They are often applied, as would a traditional current limiting fuse, to limit current magnitude and duration from a specific source and protect one feeder or piece of equipment. Reactor bypass and tie closure applications and more unique to the TCL devices due to their high continuous current capability and low losses.

### B. *Operation*

Before a discussion of their usage, a review of their operation is in order. Conceptually, the TCL is a high-speed switch that carries the continuous current. Upon sensing of a fault and response by the electronic triggering logic, the switch is opened and the current is forced into a current-limiting fuse which interrupts the circuit. See Fig. 1.

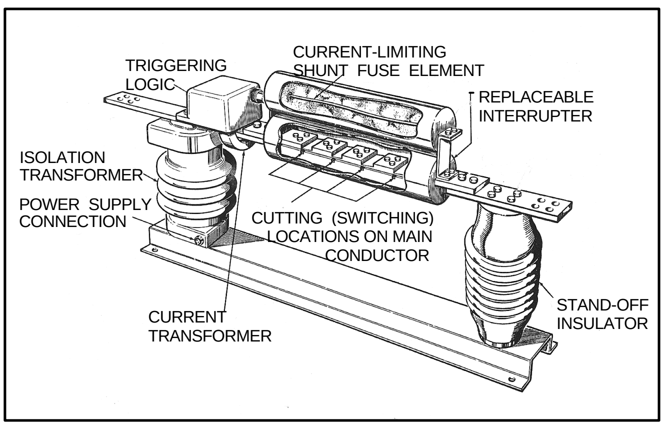


Figure 1. Layout of a Triggered Current Limiter

These devices are characterized by a primary conduction path, which electrically parallels a current limiting fuse of very high energy absorption capability and low melting $I^2t$. Approximately 0.1% of the continuous current flows through the shunt fuse in its normal state due to its resistance versus that of the primary TCL current path – a busbar. 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 shunt current-limiting fuse and its rapid interruption. The interrupt process of this shunt fuse is typical of the traditional current-limiting fuse with 1/4 cycle extinction of symmetrical and 1/2 cycle extinction of asymmetrical faults. The point of actual current limitation is often well in advance of the time of extinction. Note that this is not at the natural current-zero point at which most circuit breakers, switches, reclosers and expulsion-type fuses interrupt. The one exception to this is the reactor bypass application where the TCL is clearing against only partial system voltage across the reactor. In this case the clearing time is typically only a few hundred microseconds after occurrence of the peak let-through condition. The operating technology of TCL's has also been discussed in much greater detail in a number of the references [1][2].

### C. Coordination

From a coordination standpoint, the TCL's are catastrophic protection devices; whereby, the lower level fault currents are cleared by other protection devices operating within their prescribed ratings per their standard coordination curves. It is only when the fault capabilities of these other devices are at the point of being exceeded that the TCL triggering logic is typically set to take over and clear the circuit. Another factor to consider is that the continuous current is, for all practical purposes, completely independent of the current-limiting performance of the device. Since these are electronically sensed and triggered units, their operating criteria is preset and not dependent on time versus current, temperature, element size (or melting $I^2t$) or preconditions. The units described are not dependent on rate-of-rise of fault current, but instead, are responsive to magnitude. Specifics of fault sensing and trigger level setting as well as the methodology of trigger level selection are topics too lengthy for proper coverage and will not be discussed in this paper. They are reviewed at greater length in other literature [1][4][6].

### D. Energy Limitation

From a fault damage perspective, the TCL's provide a tremendous reduction from non-current-limiting devices such as a circuit breaker. The let-through $I^2t$ is approximately proportional to the fault energy and is a common measure of damage assessment. A 5-cycle interruption of a 40kA rms, symmetrical single-phase fault by a circuit breaker will result in a let-through $I^2t$ of $133 \times 10^6$ ampere-squared seconds. A TCL will similarly result in a maximum let-through $I^2t$ of $600 \times 10^3$ ampere-squared seconds – a reduction to 4.5% of the breaker's [1].

The Triggered Current Limiters are useful not only as stand-alone, but also as complementary devices to a number of the techniques commonly employed in the protection world.

## II. Reactor Bypass

### A. Reactor Limitations

The application of reactors to a power system is a common and effective solution to short circuit control. Unfortunately, reactors contribute two disturbing elements to a circuit. One, they consume substantial energy [3][7]. Two, they upset the system's voltage regulation. Consider the regulation difficulties that a reactor introduces into a system. Under loaded conditions, regulating voltage drops to below 95% are not uncommon. But this 5% voltage drop can reduce the efficiency of equipment by nearly 10% and even more in the case of lighting systems. This is in addition to the direct energy loss of the reactor itself. It is a substantial reduction, which may not be tolerable. It may only be annoying, as the flicker of lights. Or worse, it may prevent startup of large motors etc.

### B. A Synergistic Effect

Bypassing the Reactor with a Triggered Current Limiter can, however, mitigate these difficulties. The key here is that this combination maintains the benefits of the reactor without the operational drawbacks. It eliminates the continual energy losses related to the resistive portion of the reactor's impedance, and it eliminates the regulating voltage across the reactor since the impedance of the TCL is measured in micro-ohms. Furthermore, the reactor bypass scheme eliminates the one major drawback of utilizing the fuse by itself, specifically, that once it has operated all downstream equipment is de-energized. The reactor is commutated into the circuit by the TCL, during the fault, to limit current within the breaker's interrupt capability. Once the breaker clears the fault; however, continuity to the remainder of the system is maintained through the reactor. This is crucial to industrial facilities with critical processes and for utilities – particularly on auxiliary systems in generating facilities. While a more costly scheme than TCL's or reactors alone, this technique can avoid the far greater costs associated with a complete shutdown of a process or a critical operation. Reactor bypass applications account for approximately 30% of the TCL's.

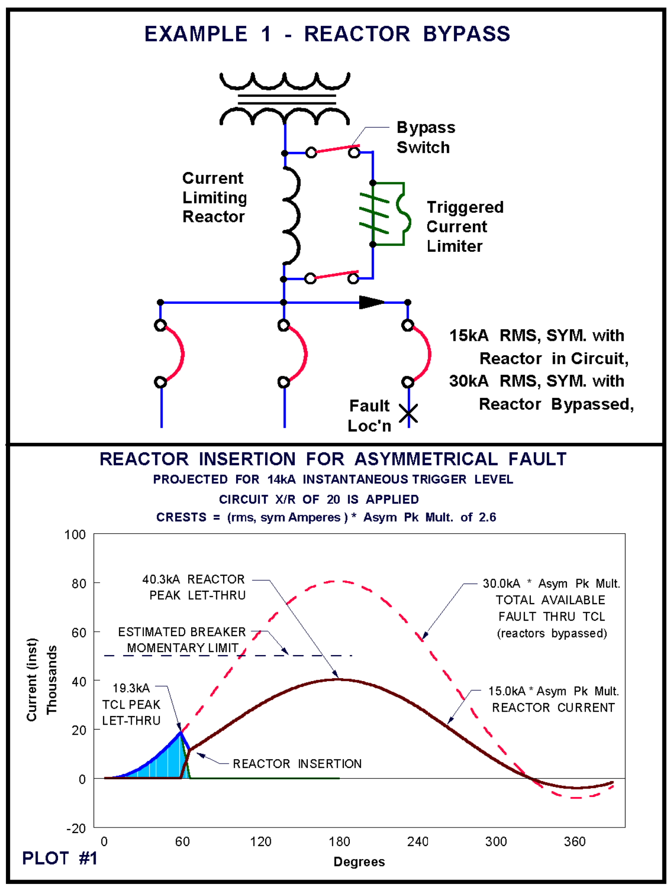

Figure 2: Example 1 and Plot 1 for Reactor Bypass

## C. Reactor Bypass Example

Consider fig.2, a common application where the user has a circuit breaker interrupt limitation of 20kA rms, symmetrical. The reactor is sized to reduce the prospective fault current of 30kA down to 16kA. The associated peak momentary current that the circuit breaker is capable of will be approximately 2.7 times the rms, symmetrical value of its interrupt rating. Upon occurrence of a fault, the TCL operates and the fault current is switched from the main conduction path of the TCL to the reactor. The reactor limits the fault magnitude to a prospective of 16kA rms, symmetrical, within the equipment ratings both in momentary and interrupt duty. The downstream equipment then clears the lessened fault level. After the fault is cleared, the reactor continues to conduct load current to the other loads on the system, such that the critical processes of other circuits through the reactor are not shut down or otherwise compromised. Power to other critical loads is not lost as would happen with the TCL itself. The bypass switches are then opened to isolate the TCL and change the expended interrupter. Following replacement, the bypass switches are closed to re-bypass the reactor. In the example one should note that the peak let-through current to the system is a function of the reactor impedance. The peak is typically not that of the TCL.

## D. Application Considerations

Conditions that must be considered which are specific to applying the TCL in parallel with a reactor are as follows:

1. The reactor circuit must be practical to begin with, in order to be successful with the TCL.
2. Consideration must be given to single-phase and 2-phase faults.
3. Isolate the live system during fuse replacement.
4. Response of the system to reactor insertion must be reviewed.

CONDITION 1, if the circuit is not practical as a reactor circuit alone, it will not be successful from a reactor bypass perspective. In other words, the reactors must be of sufficient reactance value to limit the fault currents within the equipment ratings. They must be of sufficient fault and continuous current capability to perform their function. In addition, the impedance must not be so high that the voltage drop across the reactor inhibits proper system operation.

Note that there may be cases where the reactor impedance required may be so high that its use is impractical. In these cases, the TCL alone can usually perform the protection function, but without the benefits of a reactor in parallel.

CONDITION 2, a major 3-phase fault will cause operation of all three fault limiters and thereby insert all three reactor phases. The potential user must assess the needs from the single and two-phase fault perspective. In other words, can the system, when carrying full load, operate without difficulty with the voltage imbalance imposed by the insertion of only one or two reactors, while the remaining reactors are bypassed by a TCL? More commonly, the system would have difficulties if balance were not maintained between all three phases. Refer to the one-line diagram in fig. 1. Note that there is an isolation switch at each end of the TCL. If one of these is configured with three-phase tripping and fault interrupt capability, it can be tripped by the TCL controls to insert the remaining reactor(s). The selection of the switch or breaker will not be discussed in detail here but it should be noted that the duty required of this device is typically commutating load (or limited overload) current at only the corresponding regulating voltage imposed by that current through the reactor. The fault will already have been cleared by either the TCL (and current through that phase no longer exists) or by the more immediate protection device near the fault. Some TCL users apply a circuit breaker at one of the isolation switch locations. Others apply lower rated devices. In order to support this function, the TCL has a relay monitoring each individual phase of the unit. If any phase is triggered, the relay will give a corresponding transfer. These relays have two sets of "dry" form C (dpdt) contacts for customer control interface. The response time of the relay can be as little as 2 cycles.

If the system does not have a difficulty with system imbalance, the user has two choices. They can install the isolation switches, one having at least loadbreak capability, and isolate the system without a shutdown during the TCL interrupter replacement. Alternatively, they can avoid the cost of the isolation switches by operating through the reactors until the system can be conveniently de-energized. Users not requiring full balance often prefer the cost savings of the latter case.

It should be noted that if all three phases of the TCL are not triggered, that there is no need to replace the remaining untriggered phases as is common with current limiting fuses. They are conducting through a busbar system, not a fuse element. A fuse element alone can be damaged or its characteristics altered by limited fault conditions that do not melt it.

An alternative means to tripping an isolation switch should also be noted in this paper for three-phase reactor insertion. This is the concept of three-phase triggering of the TCL interrupters. For a single or two-phase fault one can apply a set of "pulse transformers" between phases. Thereby, for a fault with an associated operation of any one phase, the same triggering pulse is also conducted through the pulse transformers to the adjacent phases such that all three are operated. This is not the preferred method for a number of reasons. First, it is causing the non-faulted phases to attempt to be cleared by a TCL at what may be a very modest current level. The shunt current limiting fuse of the TCL may not melt for a low current or may take an unacceptably long time. The shunt fuse may even attempt to clear a current for which it is not designed, as these are typically "back-up" type current limiting fuses with a minimum clear rating. This contrasts with a known response of tripping an isolation switch. Second, the isolation switches are generally part of the system already. The cost of having one of the two isolation switches configured with three phase trip and limited fault interrupt capability is generally not a substantial cost adder when considering the overall system. This additional cost is also mitigated by the fewer number of interrupters used during the life of the system. One or two single or two-phase faults may totally offset the cost of the preferred system of operating the isolation switch.

CONDITION 3 is concerned with replacement of the triggered interrupters. The concept here is generally that it is desirable to replace the TCL interrupters without de-energizing the system and shutting down critical processes. As noted in the previous section, the system is generally configured with two isolation switches for that purpose. Some characteristics of those switches are also discussed there. Those performing the work to replace the interrupters should isolate, ground and further protect the workers in full accordance with applicable codes and practices.

CONDITION 4, a frequent question concerns the transient response of the system during the insertion of a reactor. The exact response falls into the realm of analysis for the systems engineer who has the data and characteristics specific to that application. From an overall perspective, however, one must consider that the system is already undergoing a transient response due to the fault itself. Considering the clearing characteristic as depicted in Fig. 2, plot 1, the reactor is commutated into the circuit at a relatively early stage in the fault process. The commutation at this stage is certainly of less significance than at some later stage, at a higher current level. Over the history of the use of TCL's in a reactor bypass application, no disturbances specific to the insertion of a reactor have been noted.

## III. Bus Tie Closure

### A. *Why a Tie Closure*

Often the power system engineer is facing a dilemma. It may be a case of trying to start a large motor, or to better balance transformer loads, or to share the output of a generator with an adjacent bus. The overall system may possess sufficient capacity to meet all of the needs if the tie(s) were closed. However, tie closure results in fault currents from both buses and these may exceed the fault ratings of the system. Extensive replacement of equipment may be cost prohibitive. The traditional, meltable current limiting fuse in this role is uncommon, primarily because of its low continuous current capability. As a current limiting device capable of very high continuous currents, the TCL excels in this role – its most common application. The tie can commonly be closed through a TCL without replacement of equipment on either bus and without exceeding equipment momentary or interrupt ratings [1][5].

Upon occurrence of a fault, the TCL severs the tie in a current limiting fashion; whereby, that portion of fault current available through it is interrupted. The magnitude is thus reduced. This means that at some time (e.g. 2 to 5 cycles) after the TCL's interruption, a downstream device will clear the "residual" fault current, that current which was not available through the TCL.

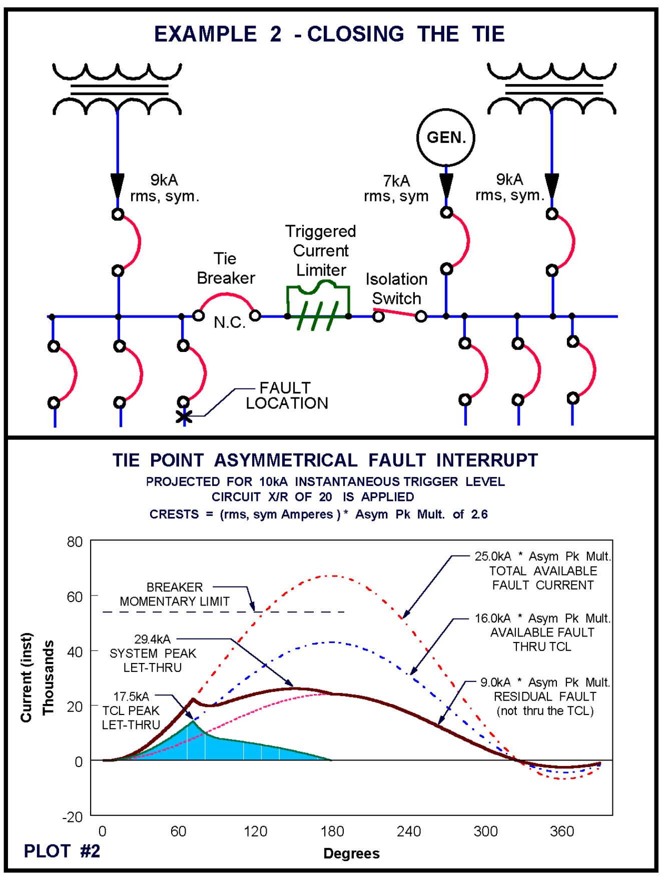


Figure 3: Example 2 and Plot 2 for Bus Tie Application

### B. *Tie Closure Example*

Consider the typical system in Fig. 3, Example 2. It portrays a closed system tie. We also have a cogenerator on one side of the tie, as is increasingly common. Assume that a fault occurs at the location shown. We have 16kA rms, symmetrical available through the Triggered Current Limiter for a total of 25kA. The equipment limit is 20kA. Available currents on both sides of the tie are shown in the plot as well as the total to the fault. Should a fault occur at the location shown, the TCL will sense, trigger and interrupt the available current through it. Following the TCL clearing, the buses are separated and the downstream breaker can safely interrupt the "residual fault," which is still supplied by the left source transformer. It should be noted that the engineer may need to re-evaluate the residual current contributions following the TCL clearing since both transformers may be connected to the same source, of some finite impedance, and the current may increase in the residual branch. While load shedding may be necessary as a temporary measure to sustain the left bus, critical processes or operations are commonly not dropped. It is simply split into two systems on a temporary basis. The tie breaker can be opened by the trip indicating relay of the TCL controls as discussed in the Reactor Paralleling section. This would prevent a possible single-phasing condition for those faults. Note the disconnect switch to the right side of the TCL. Opening this and the tie breaker will enable replacement of the expended Limiter without de-energizing either bus.

### C. *Plotting the Fault Wave*

Traditionally, when there are parallel sources to a fault and a current limiting fuse protects one, an engineer will determine the peak let-through from the fuse, via manufacturers published curves, and add this to the peak asymmetrical crest from the other sources. The fuse let-through from charts is a value unrelated to the angle of fault initiation (level of asymmetry). It is a maximum value, which may not in itself be totally accurate for that specific condition, and does not relate to the timing of the fault wave. While this method can be applied with TCL devices with conservative results, use of the computer as a tool presents a clearer picture of what is happening in the proper time perspective. Since the TCL is a precision triggered device, the computer can project the let-through for any specific fault magnitude, system X/R and angle of initiation with good accuracy. This can be superimposed with other fault current waves that are not incident through the TCL, to give a more exacting profile, as in the associated plot. This is presently performed for virtually all fault situations for any user. It permits the user to visualize what is occurring without much guesswork.

Current values in the associated plot are in instantaneous terms. This fault is depicted under fully asymmetrical conditions for a circuit X/R of 20 (a midrange value) which will yield asymmetrical crests of about 2.6 times the rms, symmetrical value. The upper curve is the total prospective fault current. The shaded area depicts the TCL's current profile. The clearing portion of the TCL plot, as generated by the computer, is based upon the specifics of the fault conditions combined with fuse operational characteristics. 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 TCL), we can project the profile of the instantaneous currents to the fault, the heavy line. Note that the system peak does not occur at the same time as peak fuse let-thru in this example. Also, it is not equivalent to the peak let-thru of the TCL 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 TCL. Preconditions and accuracy prevent these plots with traditional meltable-element fuses. With the aid of a computer, however, these plots can be readily generated for virtually all TCL applications.

*D. Application Considerations*

Conditions specific to the bus tie closure application that should be considered are as follows:

1. Rating of the TCL,
2. Single-phase fault response,
3. System response after TCL interrupt,

CONDITION 1, when selecting the TCL for a tie position, its interrupt rating does not necessarily need to exceed the total available fault current of the system. Only a portion of the total available fault current will be available through the TCL. Often a lesser rating, in excess of any foreseeable duty in the tie, will suffice.

CONDITION 2 concerns the system response to a single-phase or two-phase fault. Unlike the tripping of a circuit breaker that will open all three phases and not leave a potential single-phasing condition, interruption of a TCL, like a fuse, may be a single-phase operation. Only the phase(s) reaching the trigger level will trigger and interrupt. After the downstream breaker clears the “residual” current, however, remaining untriggered phases of the TCL will continue to conduct and may result in an unacceptable imbalance in phase currents through the tie. Standard voltage sensing relay techniques may not readily detect the difficulty since sources reestablish full voltage at both ends of the triggered TCL after the fault is cleared.

The TCL provides the relaying means in the user interface of its control system for this purpose. As mentioned previously, it has a relay monitoring each individual phase of the unit. If any phase is triggered, the corresponding relay will transfer. These relays have two sets of “dry” form C (dpdt) contacts for customer use. The response time of the relay can be as little as 2 cycles. The user generally configures these contacts such that any TCL operation will cause the tie breaker to trip and thus avoid a single-phasing condition.

CONDITION 3, as mentioned prior, the current in the residual current branch may change as the TCL interrupts. The available fault currents may come from a variety of sources including transformers, cogenerators, motor backfeed etc. The case that may require an additional review concerns those sources that may have an alternate path or means of supplying fault current after the TCL has operated. Consider the two transformers in the prior example (shown as impedances Z2 and Z3 in fig. 4). If they were in-turn connected to the same source (via impedance Z1), the associated fault current would split between Z2 and Z3 based on their values. However, if either Z2 or Z3 becomes infinite (due to TCL interruption of that branch), the current in the remaining transformer will increase. Therefore, the “residual” current also increases and the switchgear must also be able to interrupt this additional contribution.

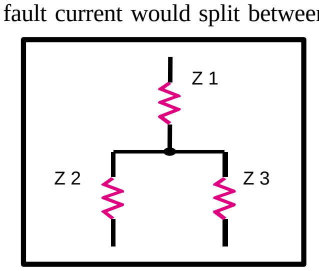


Figure 4. Source Divider

## IV. Power Quality Improvement

*A. The Problem*

Consider the system depicted in Fig. 5. It has two facilities (or buses) supplied from the same source. Each of the facilities may contain motors, computers, lighting systems or other critical loads. If a fault occurs as shown, however, not only will the faulted facility be affected, but also the unfaulted. Typical clearing times for circuit breakers are from 3 to 5 cycles. This contrasts with lighting systems that may drop out and require a time-consuming restart with as little as ½ cycle outage time. Computers may be protected by UPS systems, but UPS systems are often not as commonly employed on machine tools or other manufacturing equipment. Motors may fall out of synchronism and their starters drop out by the three cycle point. This is particularly critical in process industries where a momentary power disturbance can result in a costly shutdown.

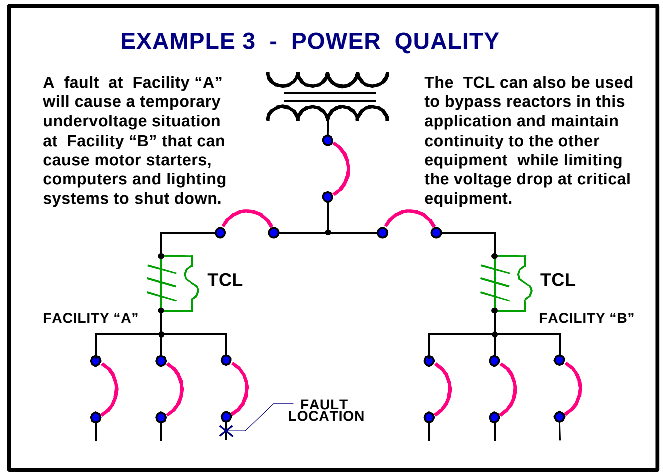


FIGURE 5 Power Quality Example

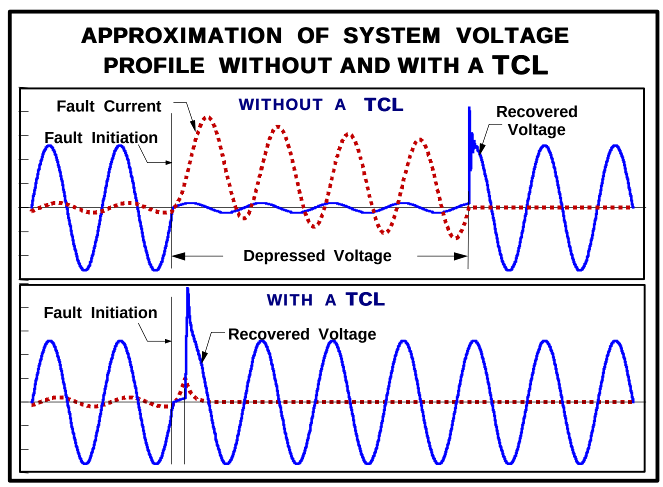


Figure 6: System Voltage During Fault

*B. Limiting Voltage Depression*

In fig.6 the system voltage is depicted for fault conditions with and without a TCL. As can readily be noted for the upper plot, the system voltage will be depressed during the fault period, which may remain until the protective device clears the circuit. Explicit percentages of depressed voltage versus operating voltage can not be given here as they are specific to the system characteristics, fault location and to the fault impedance. It can be noted in the lower plot, however, that the TCL limits the time to a very short period. Even on an asymmetrical fault, where the fault current extinction point will be maximized for the TCL at ½cycle, the point of shunt fuse melt and current limitation is typically well in advance of current extinction. The voltage recovery of the system coincides with the melt and subsequent clearing time. Data for the plot has been taken from a typical TCL interruption trace. It can be seen that the condition of depressed voltage is minimal with this device. Dropout of equipment on the adjacent bus is not expected.

What are the affects of cogenerators, or other sources in regard to supporting voltage on the unfaulted bus? This would need to be considered on a case by case basis by the engineer. Such factors as the specific bus and cable impedances, cogenerator size and fault characteristic time constants are all relevant. The application of reactors to limit fault current, and thus support voltage on the adjacent bus is a possibility. Again, here it is the specifics of the system versus the reactor impedance that will determine its practicality. The concept is to provide continuity to the faulted bus after fault clearing. While certain equipment will be dropped, those that can ride through the depressed voltage state will not have been cut off by the TCL, as without the reactor. The reactor bypass concepts are reviewed earlier in this paper.

Applications of TCL's for power quality considerations are newer than the above topics with ones specifically dating back five years.

## V. Conclusions

The Triggered Current Limiter can be an effective tool for high continuous current systems. It can be applied in traditional roles as one would apply a current limiting fuse or in unique roles. Among these are reactor bypass, tie closure and power quality applications. Each role has its own conditions for successful application. Likewise, each has specific benefits.

The TCL is a predictable device where its performance in the system can be modeled by computers prior to their application. Analysis by computer can provide a more accurate insight into the actual conditions than by traditional analysis techniques.

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## Biography


**John S. Schaffer** (S'73-M'82-SM'90) received the BSEE and BSME degrees from Marquette University in 1974 and 1976 respectively and the MBA degree from Lewis University in 1988.

An 18 year employee of G&W Electric company, he has held the positions of Sr. Development Engineer, Manager of Switchgear and Fuse Engineering, and Technical Director of Project Engineering. He has been the General Manager of its System Protection Division since 1992. Prior to joining G&W, he was affiliated with Allis-Chalmers Corporation for 7 years, in the engineering of high voltage circuit breakers, motors and DC traction systems.

Mr. Schaffer is a member of the IEEE High Voltage Fuse Subcommittee where he is active in a number of working groups on fuse standards. He is also a member of NEMA's High Voltage Fuse Technical Committee and other organizations.

He has authored and co-authored several technical papers on fusing and switchgear topics and has received a number of patents in these areas. He is a registered professional engineer in the state of Wisconsin.