Arc-Flash Problems in Low-Voltage Switchboards A Case Study in Arc Fault Protection

Amit Jindal, CMD, Prateek S. Chauhan, Dy. GM (Operations)
Shivalic Power Control (P) Ltd., Faridabad, Haryana

Abstract— offshore installations often push switchgear to the limit of their rated current and short-circuit withstanding capacity and, in some cases, even above. This is due to the increase in the number of electrically driven loads and the severe space and weight restrictions offshore. The same is being seen now for onshore installations where there is often limited space for new production facilities. Expansion of existing plants results in both increased rated and short-circuit currents and, in some cases, more complex switching arrangements, some of which could cause switchgear ratings to be exceeded. There are several techniques that can be used to cope with such situations. In some cases, it is sufficient to provide interlocking to prevent unacceptable operating conditions from occurring. In other cases, it is necessary to add pyrotechnic fault current limiters (FCLs) to prevent equipment destruction should a short circuit occur. As with all equipment, it is necessary to understand how FCLs operate in order to be sure that they are correctly integrated into the power system.This paper will review several techniques that have been used in applications to ensure switchgear integrity. There is a special focus on the correct integration of FCLs. We consider such measures to be an integral part of the switchgear, thus allowing verification of all safety features during the equipment design and testing phases Prior to arrival at site. The project specifications should include all planned future growth to ensure that the power system and switchgear be designed accordingly.

Index Terms— Fault current limiters (FCLs), short-circuit currents, switchgear.

1 Introduction

FOR industrial applications, the selection of the distribution and load voltages is ideally based on the level of rated current needed to supply the power to the plant loads. Typically, rated currents are limited to 4000 A. Judicious positioning of incoming circuits and feeders often allows the bus bar rated current to be much lower than the total current that is required to provide power to the process loads.

The maximum short-circuit current that can flow in power systems is typically 10–20 times the rated current of the main switchgear supplying the plant. When a fault occurs, the current flowing into it will be the sum of all of the current produced by the connected rotating equipment, this being the generators including those of the utility, and all the motors in service.
When either the rated current or the maximum short-circuit current exceeds the available switchgear ratings, the normal solution is to select a higher voltage level, thus reducing both the rated current and the short-circuit current to acceptable values.

For offshore and floating installations, this is often not an acceptable solution since it requires additional transformers and switchgear cubicles.

Additional equipment means additional space and weight, which will result in a much higher cost of the structure.

In addition, there may be certain switching configurations that are to be avoided or only allowed for a very short time. It is necessary to define the methods to operate equipment safely, although the equipment ratings may potentially be exceeded.

Examples of such situations and methods that can be used are given in Section V of this paper.
When the issue is short-circuiting currents, which could exceed the switchgear ratings, it is sometimes possible to avoid problems by using transformers with higher impedance or by installing current-limiting reactors. The main disadvantage of both of these solutions is the additional impedance that is inserted in the power system that can have negative effects on motor starting and system stability. A solution that has been often used on floating production storage offloading (FPSO) is the insertion of FCLs at strategic locations in the power system. As described in the following, these devices are very fast acting, do not introduce additional impedances, and will control the flow of fault current within the power system. Thus, the maximum fault current at any location within the power system can be kept within acceptable limits. They do however take up space and add weight.
Due to the fact that FCLs are very fast, the power system must be designed to prevent transient currents that sometimes occur during normal operation from flowing through them.

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2 SHORT-CIRCUIT CURRENTS

2.1 Review Stage

Short-circuit currents flow when insulation breakdown occurs between energized conductors operating at different potentials.

In three-phase power systems, the different types of short circuits (three phase, two phase, and single phase) will result in different values of maximum available short-circuit current.

For equipment ratings, it is necessary to consider the worst case which, for faults close to generators could be two-phase faults.

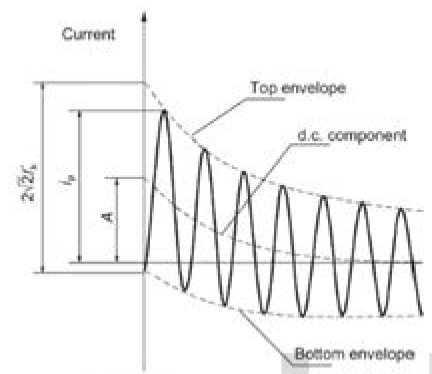

Fig. 1. Short-circuit current close to generator.

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Short-circuit currents in medium-voltage (U > 1 kV) power systems generally have a very low power factor since the system inductive reactance is much higher than the system resistance.

The inductance of cables, overhead lines and transformers is constant, but that of rotating machines is not. The sub transient reactance is used to determine the maximum contribution from generators, and for this short period (100–200 ms), the negative sequence impedance of the generator can be considered constant.
The other factor that determines the maximum peak value of the short-circuit current is the direct current component *i*dc.

The time constant of *i*dc is important since it will determine the amplitude of the dc component at the time the symmetrical component has reached its highest value and the addition of both results in the maximum peak short-circuit current *ip*.

The time constant is often in the range of 120 ms since generator resistance is kept low to reduce losses. Fig. 1 shows the waveform of the short-circuit current due to a fault close to a generator.

The dc component contributes to the interrupting duty of circuit breakers and must be taken into account in their selection [1].

All equipment must be able to withstand the mechanical stresses caused by the flow of *ip* through the system. Due to the high dc component, the interrupting current *Ib* must also be considered in order to be sure that the circuit breakers will be able to clear severe faults.

There are various internationally accepted methods for calculating short-circuits currents. The most important part of calculations is getting the correct data and knowing how the power system is to be operated. This information must be carefully documented in the short-circuit calculation reports.

3 FCL OPERATION

As a quick introduction, FCLs are a specialized form of current-limiting fuse—essentially hybrid devices that allow for both high continuous current ratings required in many medium voltage applications and for fast clearing of high-level fault currents. As an example, traditional current-limiting fuses are commonly limited to about 300 A continuous in the 10–15 kV category, but FCL ratings through 5000 A continuous are commercially available in this voltage range and can potentially

Fig. 2. 15.5-kV 3000-A FCL installed in offshore lineup.

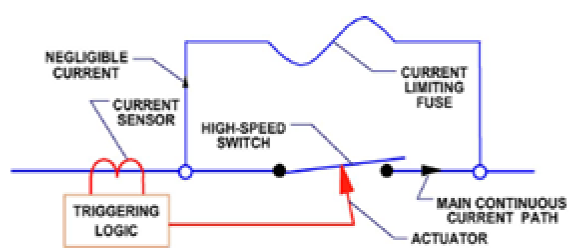

Fig. 3. Untriggered FCL, normal operation.

Be extrapolated to yet higher levels. Higher and lower voltage ranges of FCLs are available in a wide range of continuous current ratings.
FCLs are commonly capable of interrupt duties well beyond the traditional 50 kA ratings of traditional fuses. Further, even below 50 kA, they must be capable of absorbing much higher fault energy than a traditional current-limiting fuse since their melt does not begin at the start of the fault current but at some elevated current level following the triggering and commutation described in the following. Timing becomes critical since one delays operation until the proper triggering current levels

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are attained, and yet must melt and limit the total peak currents in an effective fashion.

Fig. 2 shows an FCL installed inside a switchgear lineup.
It is connected to the switchgear bus bar top and bottom, and the sensing and triggering equipment can be seen above the cartridges housing the active devices described hereafter.

A. Basic Operation

The FCL utilizes a separate continuous current path in parallel with the higher impedance current-limiting fuse element(s).

Thereby, in its normal operating condition (see Fig. 3), only a very small portion of the continuous current flows through the current-limiting fuse, with the remainder through the main conductor.
Upon reaching over current conditions meeting the fault-level triggering criteria, a pyrotechnic charge is activated as shown in Fig. 4. Its purpose is to sever the main conductor and initiate commutation of all current to the current-limiting fuse element.

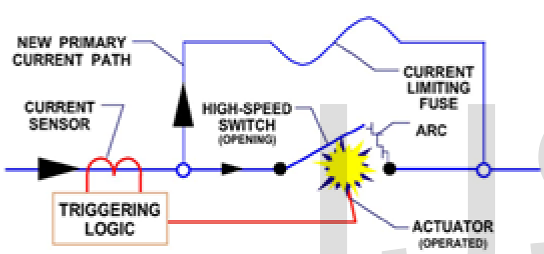

Fig. 4. Triggered FCL during commutation.

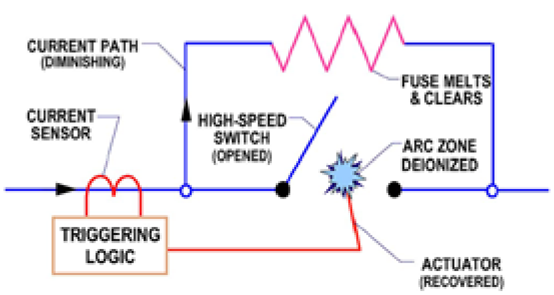

Fig. 5. Triggered FCL at time of clearing.

This is, in effect, a high-speed switching operation to insert the current-limiting fuse. The reason for the pyrotechnics is that they yield the required speed of switching (commutation) at the main conductor at the time of triggering.
The fuse melt is not instantaneous but is a coordinated function of the FCL design. The fault current continues to rise after triggering until melting of the fuse is completed. The melting time permits the minimum dielectric recovery period at the main conductor to be met. This period is required prior to onset of the fuse's high arc voltage. It enables the severed main conductor to withstand the arc voltage imposed across it. As a result, the trigger level is not the peak-current cutoff point but Instead the start of the interrupt process.

At the point of melting, the arc voltage of the fuse rises to limit the fault current and start its reduction. While this action quickly reduces the current, it does not immediately force it to zero. The arcing of the fuse introduces a high resistance into the fault circuit, as shown in Fig. 5.

This added resistance forces a shift of the current wave to be in phase with the voltage. As the current value continues to fall, the arc voltage also falls and more closely follows the system voltage. Thereby, the total extinction of the fault in most any current-limiting fuse will occur at or shortly before a zero voltage. This is not to be confused with the zero current clearing of breakers and other switching devices. It is generally well before the peak currents are attained in the rest of the system.

B. Current Limitation Plot

The current that flows through the FCL when it operates is shown in Fig. 6. Prior to operation of the FCL, the unlimited

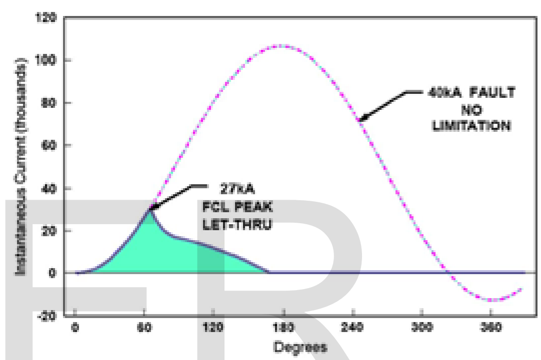

Fig. 6. Typical clearing plot of asymmetrical fault.

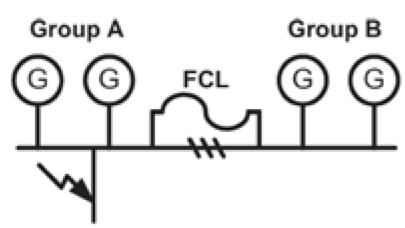

Fig. 7. FCL installed in bus tie.

Current flows following the "available fault" curve. Upon actuation of the FCL, the current is limited by the fuse to the shaded area. At the first zero voltage (which corresponds to maximum current in an inductive circuit) the current through the FCL is completely interrupted. This occurs at 1/4 cycle for a purely symmetrical fault to 1/2 cycle for a fully asymmetrical fault.

Very often, FCLs are installed in bus ties in order to block the contribution to short-circuit current from sources connected to other buses. Fig. 7 shows a typical installation, and the clearing plot for the FCL will exhibit the initial fault current wave and its limited value. In many cases, other system currents that are not limited by the FCL will be added to the plot, so that the client has a better perspective of the total effect. Most commonly, the plots are done under fully asymmetrical conditions that can accurately depict the peak values. Note that the cutoff and peak values are in instantaneous amperes.

It is typically most helpful to the user to see the effects of the other sources superimposed and added to those through the FCL. This cannot normally be done with traditional current limiting fuses due to the preconditions that those devices may have been exposed to. The super positioning of sources is depicted in Fig. 8. In this case, the part of the original source (Group B in Fig. 7) is interrupted. One can clearly note that the peak cutoff of the FCL does not coincide in time with the other current, which is not going through the FCL. Thus, the peak currents are not directly additive.

These plots (see Fig. 8) can become quite complex, particularly when multiple FCLs are called upon to simultaneously clear on the same fault. It allows one to analyze the additive peaks in order to ensure that the total values do not exceed.

The peak limits of the equipment. While the peaks may be maintained within the breaker limits, this does not always 2644 IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 51, NO. 3, MAY/JUNE 2015

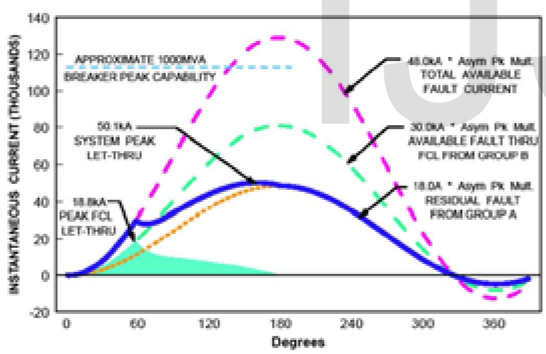

Fig. 8. FCL interrupts contribution from group B.

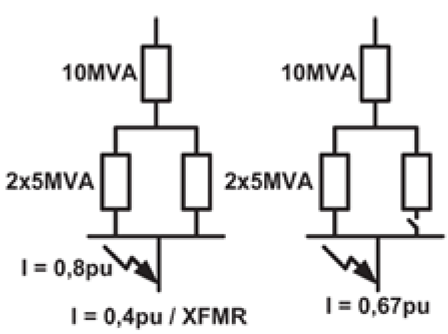

Fig. 9. Increase in individual fault contribution after removal of parallel source.

Ensure an acceptable application. Considering the case where there are two sizeable sources on each side of a bus tie, one must be careful that the energy in the resultant wave, even after FCL interruption, does not exceed the capabilities of the breakers.
The FCL manufacturer can provide guidance here.
C. Other Considerations

One must be careful in systems with multiple transformer sources connected to a singular transformer supply. The utility supply has certain source impedance that will limit the maximum fault current through parallel transformers.

Following the operation of the FCL, one of the parallel transformer contributions is interrupted, and without the parallel supply, the contribution from the remaining transformer will increase. This is shown in Fig. 9 where the contribution of each transformer (XFMR) in parallel is 0.4 p.u. but after removing one XFMR from the circuit, the fault current through the remaining XFMR increases to 0.67 p.u. Occasionally, one will find that the associated increase will yield a fault current still in excess of equipment ratings.

4 APPLICATION OF THE FCL

In order to ensure a successful application of the FCL, careful consideration of a number of conditions must be taken. While the use of these devices can provide much valued extension of the protection limits of the system, one must have a thorough analysis of the system performed before finalizing the plan.

It is most highly recommended that this be shared with the manufacturer of the FCL, who has extensive experience in their application, well beyond that of clients and most consultants.

This preliminary system analysis may predate the order and delivery of these devices by a few years, to enable the system designers to confirm the protection and complete other aspects of the system design.

The analysis is ideally done in the early stages of system design so that, while some fault information is tentative, a basic concept can be developed and the proper devices selected. As an example, for a 10–15-kV class FCL of a continuous current of 2000–3150 A, there can be numerous versions of the device that can affect both cost and performance.
It is therefore best to get the FCL manufacturer involved early in the process as the trigger level selection is not intuitively obvious. It must be low enough to protect the equipment but high enough to let normal operating currents flow without riskof unwanted triggering. The consultant and their client may often benefit from up-front guidance as to what can and cannot be done, as well as what other considerations may affect their design.

A. *Location of the FCL*

It is generally desired to remove as little available power from utility or generator sources as necessary to protect the system.

In that way, after clearing of the fault by the FCL, the power supply to the rest of the system can be maintained. One may ask whether it is best to place the FCL in a bus tie or on one major source feeding the system with a closed tie.

In some cases, one may protect a single bus by removing a single feed from that bus, but this is the simplest example. This is most common in utility distribution systems.
More common in industrial and utility generating systems are major buses with multiple high fault current sources connected.

As the systems increase in size, they are typified by ties between two or more buses. These ties are normally closed such that there is only one power system at the site. If a FCL is used in a bus tie, as shown in Fig. 7, an opening of the bus tie under fault
Conditions will result in segmenting of that system. If power supplies on each side of the tie are sufficient for maintaining their load, this can minimize disruption.
Bus-tie applications of FCLs are the most common usage. In some cases, the bus tie is relatively inaccessible for later incorporation of one of these devices. In that case, the interruption of a suitable source (a generator or utility transformer) by the FCL under fault conditions is not uncommon. In some cases, interruption of the back feed from a large load may be considered but is the least common application.
Some systems have multiple buses in series with a FCL in each tie point. There are various forms of selectivity that may minimize the number of FCLs involved in clearing a fault event. Natural selectivity is a simple technique and relies on the portion of cutoff current from one limiter preventing an additional unit from triggering. This may be difficult to achieve in systems configured as a closed loop. Since there is no point at which there are two open ends, there is a greater likelihood of additional triggering that might be avoided with an open loop.

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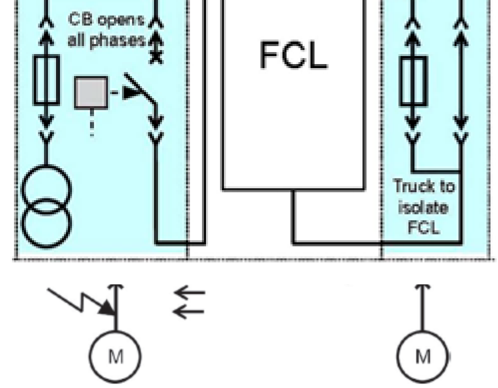

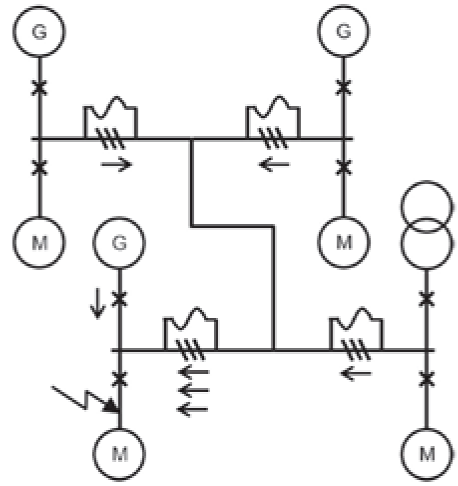

Fig. 11. Bus configuration with common tie point.

Another format that has been successfully applied is the use of FCLs in systems with multiple buses tied to a singular tie point. This has been accomplished with either generators or utility transformers tied to each bus, and a FCL adjacent to the tie point. A breaker will connect the tie from the FCL to the lineup of that bus, and a non load break device between the tie point and the FCL will provide isolation as shown in Fig. 10.
This technique will typically have rather high fault currents into the tie point that are cleared by a single FCL connected in a simple sensing scheme. This common point can also be beneficial
When synchronizing generators. A separate synchronizing bus may be avoided. This format maximizes the trigger level of the FCL and results in only one FCL being triggered since the current from any individual bus to the tie point will typically be less than the trigger level of the associated FCL. This technique is most effective in systems with four or more buses connected to the single tie point, as shown in Fig. 11.

When there is sufficient generation on each bus to supply the loads of each bus, operation of the FCL will often not cause any loss of production should the fault be located on the load side of a feeder breaker. If the fault is on a bus, then the complete bus will be tripped. This technique has also been applied in conjunction with bypass reactors around each FCL to maintain limited continuity following a triggering.

B. *Selection of the Trigger Level*

The calculation of trigger levels can be simple or complex. It generally takes one of two forms. These are the "direct method," and what may be termed the "proportionality method."

Major manufacturers of these devices use both, essentially in the same way. How they measure the fault current values can vary.

The exact nature of trigger level selection is suitable for a separate technical paper in its own right; therefore, only a limited presentation can be made here.

It is very important to be explicit and preferably maintain consistency in the units that pose a frame of reference of the working data in order to avoid confusion. It is most helpful to start with initial RMS, symmetrical values, and initial *X/R* values, which permit computation of the proper asymmetry values. Data including the fault current values *Ib* at the time of breaker interrupt are also helpful. These can sometimes be used to maximize the trigger levels in the calculations.
Both the direct and proportionality methods of calculation are typically based upon the interrupt capability of the gear rather than the momentary capability. This is because the gear will almost always be protected for both cases when calculated this way. While the RMS and symmetrical base of the momentary ratings are sometimes higher than associated interrupt capabilities, the opposite is not true. A check of the momentary duty is always a necessity.
The direct method simply takes the value of fault currents on an over duties bus, minus the prospective fault current value through the FCL. When this value (what is sometimes referred to as the "residual current") is subtracted from the equipment rating, this yields the allowable current through the FCL. This may then be expressed in either an RMS, symmetrical, or an instantaneous current term for use by the FCL manufacturer.
Safety and other factors can be built in at this time. Calculation by this approach will yield the most conservative results, yet these results may sometimes be impractical.

For example, if one has 37 kA on each of two buses that one wishes to connect via a bus tie, this would mean that only 3 kA would be permitted through the FCL for a 40-kA rated breaker. Many individuals attempt to calculate trigger levels based on this method and find an unsatisfactory solution. This may not be practical for a 3000-A rated bus. It is here that the alternate calculation technique is quite beneficial, yet it must be applied with caution.

The proportionality method of calculation takes a much different approach. This technique must be applied with caution since it is dependent upon factors that must always be present in order for the analysis to be valid.
First, consider that, for any fault, the actual current will be dependent upon not only the impedance of the system, *X/R*, etc., but also upon the impedance of the complete fault path.
Now, consider that within a rather small percentage, all of the sources supplying the fault during the first one-half cycle will contribute fault current in proportion to the full available fault current. Therefore, if a high impedance fault occurs that limits the actual fault current to 50% of the maximum available, each of the sources contributing fault current will be reduced to approximately 50% of its maximum respective available current for that fault location.
The concept is that, if the protected gear is capable of handling 70% of the total available fault current (that through the FCL plus the residual), then we need to trigger the FCL only when 70% of the available fault current through this FCL is exceeded. A proportion is set up whereby the ratio of the ratingof the protected gear is related to the available fault current.

This gives the allowable portion of the current available through the FCL before triggering must occur. A general format is given in the following. The condition under which the FCL needs to trigger is

$$\left(\frac{I_b}{I_k}\right) \times I_{\mathrm{FCL}} = I_T$$

where

I_b interrupt rating of the breaker in A rms, symmetrical;
I_k rms fault current at the time of breaker interrupt;
I_{FCL} fault current through the FCL at that same time;
I_T trigger level of the FCL in A rms, symmetrical.

The *IT* value is also commonly then restated in an instantaneous ampere value. Note that, if the initial values of fault current are used, rather than those at breaker interrupt, a more conservative value will generally be calculated. Again, the party selecting the trigger level must also perform a peak analysis to ensure that the peak values and the overall waveform are within the capabilities of the breakers. This is where a plot from the FCL manufacturer becomes quite useful. This simple calculation can be quite misleading since the current through the FCL may be a variable. If, for example, a group of generators is supplying current through the FCL, but when one or more is removed, the total fault current through the FCL *I*FCL is reduced as is the system total *Ik*. One will find that the trigger level value *IT* must also be reduced. As fault contributions through the FCL are further reduced, the *IT* value will asymptotically approach the value determined in the direct method calculation. This also applies to contributions from motors as they may or may not be energized at any time.
The *I*FCL value must be based upon the minimum fault current that can be guaranteed to be available through the FCL. It is best if there are major sources of fault current through the FCL in order to maintain a relatively high trigger level.

This brings us to a point of importance in getting the proper system fault information, which should include the individual fault contributions of each major source, and a lumped value for back feeds from loads on each side of the FCL. The best result is commonly from a formal fault study where all major contributions and those of sub buses can be provided.

Commercially available engineering software for doing system studies is not useful for analyzing the operation of FCLs during fault conditions. However, it is most helpful in defining the currents for FCL trigger-level analysis.

C. *System Information*

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As noted above, proper system fault information is a prerequisite for proper application and maximization of trigger level. A detailed system single-line diagram showing source transformers, load transformers, generators, large motors, capacitor banks, and the sizes of each are a good foundation.

It often entails major computer modeling and associated study to determine the fault characteristics at various locations in the system, and at various times. This can be particularly helpful but requires analysis of much data.

This need for information is not limited to simple fault current calculations. Investigation of inrush current levels, as well as a comprehensive look at potential operating states of the system, is also required. For example, in one fairly recent case, a client had five main buses that were protected by two sets of FCLs. This client potentially had 22 different operating schemes. The system analysis required an evaluation of each bus for both FCLs for all 22 schemes. The trigger levels for these schemes were determined, and as a result, the plant limited their operation to about 15 of these in order to maximize the trigger levels without necessitating an adjustment each time a variation occurred. This was coordinated with their corporate engineering staff and with the plant operations personnel. As this analysis is particularly difficult for both the client and even the experienced consultant, it is recommended that these parties coordinate the selection with the FCL manufacturer who may have some additional insight to offer.

D. *Considerations in Avoidance of Unnecessary Triggering*

First, unless one is using the FCL for arc-flash protection or fault energy limitation on a continuing basis, the device can be disabled when its protection is not needed. For example, perhaps one source is removed from the system, reducing the fault duty on the breakers to below their rating. The user must keep in mind that the fault currents through the FCL may still be sufficient to produce a triggering, although some sources are not energized, and the system is not presently over dutied.

The FCLs can be disabled locally or remotely via relay logic, programmable logic controllers (PLCs), or SCADA systems. It is necessary, however, to ensure that the FCL has been placed back into service prior to the reconnection of any sources that had temporarily been removed. Suitable interlocking to prevent dangerous conditions should be provided.

The following equipment and conditions should be treated accordingly.

Motors: Consider large motor starting currents. While many consultants and users are very concerned, it is quite rare that these become a factor, and their inrush values are generally quite predictable. It is important to supply motor sizes or inrush values when available, but these are generally not a concern for the FCLs. One reason is that, although their starting currents may be over a lengthy period, the FCLs are not a time–current device, but instead, current only.

Therefore, while starting energy may be substantial over time, affecting traditional fuses and other devices, triggering of FCLs in response to the current levels can be readily avoided.

Transformers: It is important to know the sizes of transformers that may be energized. The inrushes are calculated on a different basis than the RMS values typified in traditional fuse applications as the higher "instantaneous" values typify the FCL calculation. Each FCL manufacturer will have their own guide for allowance of inrushes on transformers. The maximum inrush current is reasonably predictable, resulting in a target hat the manufacturer can almost always (well over 99%) select a trigger level above, without detuning or disabling the device.

A limitation may be seen in large utility network systems where many transformers may be energized simultaneously, with very low trigger levels for arc flash protection requirements. This can also be coordinated with the FCL manufacturer.

Capacitor Banks and Harmonic Filters: Again, here, we have components that are rather predictable. It is rare that the peak levels of initial inrushes can cause a problem. The application must be coordinated with the manufacturer. As a note, however, while rare, the case of a capacitor bank switch with a restrict problem can yield multiples of bank voltage and elevated currents as a result of this characteristic. Currents have been known to reach the trigger level of the FCLs, which then act to protect the system. These are not a case of a mist rigger.

Further regarding capacitor switching, one must be cautious of "back-to-back" capacitor switching where high magnitude currents are conducted through the FCL. This should be planned with the FCL manufacturer and, generally when engineered up front, does not pose a problem or operating limitation.

Over voltage Surge Arrestors: These are components whose placement is important with regard to the FCLs. For petrochemical plants supplied by a utility, the arrestors are normally installed on the high-voltage equipment in the substation downto the load side of the main step-down transformers. Since the FCLs are installed at the medium voltage level, any high currents resulting from arrestor operation will not flow through the FCLs. When local generation is used, there will also not be an issue with arrestors since there is no danger of atmospheric discharges flowing into the system as there are no overhead lines.

Should there be a risk of arrestor current flowing through a FCL, this can in fairly rare cases yield a current meeting the triggering criteria. It is advisable to use arrestors with a higher yet acceptable turn-on voltage rather than lower. A known but very rare phenomenon is related to the use of other current-limiting fuses downstream of an FCL. When there are arrestors also downstream of the FCL, the arc voltage of these current-limiting fuses can cause a discharge through an arrestor and could result in a triggering of the FCL.

As the FCL is already providing current limiting protection, the use of current-limiting fuses may often be avoided, and an expulsion type might be substituted. As one may expect, many systems have arrestors, yet there are rather few operations of FCLs attributable to discharges through these.

Dead Bus Energization: This is an occasional concern, which can be checked during commissioning with a device termed a "simulator." The simulator is a device used in the FCL system without the protection of the interrupter but capable of detecting a triggering and sending a response to the control box. Consider that any bus has a fair amount of "stray capacitance" from cables, bus, bushings, etc. One can calculate cable inrushes based on various formulas. However, these and other system components have lesser amounts of capacitance than capacitor banks, which are known entities and readily calculated. These relative unknowns can produce a short-time high-magnitude high-frequency phenomenon, when connected to an adjacent bus with similar unknown characteristics. As energy levels are low, these are typically ignored and not part of the response scheme of most relays.

One would not calculate the inrush to an un energized bus (one without capacitor banks) by considering the prospective fault current in the system as it is a local discharge, essentially a back-to-back phenomenon between the energized and un energized bus, with negligible resistive or reactive impedance between them. Discharges in the tens of kilo amperes and frequencies in the hundreds through thousands of Hertz have been noted. The FCLs, may reach the trigger level, but in virtually all cases, the manufacturer has a filtering means in the sensing system to avoid a response.

During commissioning, about 30% of FCL customers request the use of a simulator to validate the correct operation of the FCL prior to the start of commercial operation. The simulator can alert one to the presence of a potential triggering condition, which one can then work around without expending an interrupter unnecessarily.

E. *Coordination and TCCs*

There are no traditional time–current characteristic (TCC) curves for most triggered FCLs. It is effectively a straight line function at the trigger level as they are cleared before 10 ms where the TCC curves start, and if not triggered, they are waiting for a breaker to clear within its operating capabilities.
Regarding coordination, these are generally current-only devices as opposed to time–current of relays and traditional fuses.

As a result, the trigger level is a "hard target" that the currents are not to exceed without operation.

5 SWITCHGEAR INTEGRITY

If Power systems must be robust. A robust system will not do things that it is not supposed to do when unexpected operating conditions occur or during component failures. Making a system robust is often more difficult than ensuring that it performs the tasks that it is to do.

For switchgear, it is necessary that all functions be executed correctly, but equally important that no incorrect switching operations can be executed. A major portion of factory acceptance testing (FAT) should be checking that no unacceptable switching operations can be executed during both normal and exceptional operating conditions.

The following examples from recent projects illustrate the thought processes that are required to ensure that inadvertent operation or single equipment failures will not result in dangerous conditions.

A. *No-Break Transfer Schemes*

Electrical equipment is designed to withstand the maximum currents and voltages that it can be subjected to. Paralleling power sources for a short time when switching between them avoids a loss of voltage and thus avoids production outages.
In many process plants, the commonly used no-break transfer scheme results in the maximum available short-circuit current exceeding the switchgear rating during the (short) time of the transfer. This has effectively become an industry standard with the risk that familiarity breeds contempt. The use of this system can only be justified by the immediate and reliable tripping of Double bus bar configuration.
One of the breakers just after the sources has been paralleled.
The very short transfer time has been deemed to reduce the risk of miss operation to an acceptable value. In some cases, this most important requirement is overlooked by the engineers designing the control logic perhaps because this type of system is used so often that particular attention is not given to ensuring correct tripping.
When the technical authority has accepted that a no-break transfer scheme be implemented that allows momentarily exceeding the short-circuit current rating of the switchgear, it is essential that the time during which the sources are connected in parallel be kept to an absolute minimum. There are several ways that this can be done but not all are equal. The increased use of intelligent electronic devices (IEDs) has added several possibilities that are sometimes used, although they can reduce the reliability of tripping.

It is recommended that the tripping of the breaker that is to be open after the transfer is completely be done directly by means of hard-wired auxiliary breaker contacts, Some designs may use the IED outputs to trip the breaker but a failure in the IED could result in the sources remaining in parallel until a maintenance engineer can manually trip the breaker. It is a good idea during the FAT to switch off the power to IEDs to check if the integrity of the switchgear could be compromised by a device failure.

B. *Load Transfer in Double Busbar Systems*

Double bus bar switchgear is occasionally used for the main switchgear in large facilities. One advantage of this system is being able to operate part of the process independently of the rest. This can be useful for maintenance and commissioning.

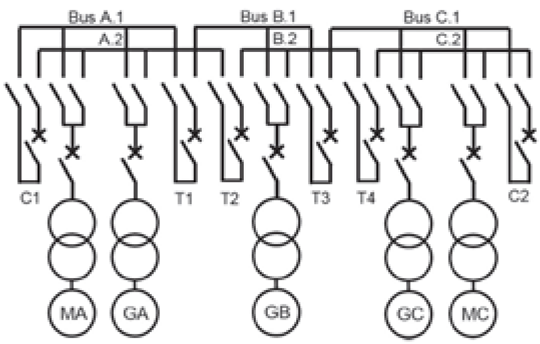

Fig. 12 shows a double busbar 36-kV gas insulated

Switchgear (GIS) lineup for a large site. Power is provided by five gas turbine generators (GTGs) with two GTGs connected to bus A, one GTG connected to bus B, and two GTGs connected to bus C. The bus bars are separated by bus-tie circuits, and there are two bus couplers, one at each end of the switchgear.

Normal operation of the GIS is with the disconnecting switches and breakers of both bus couplers and both bus ties closed.
Each feeder breaker also has two disconnections. They are used to connect the feeder and incomer breakers to either one of the bus bars. Only one of the disconnections of the feeder and incomer breakers is closed during normal operation. Paralleling of the bus bars is done only through the bus couplers, not through the disconnections associated with any feeder or incomer breaker.
To switch a load or GTG from one bus bar to another without opening the breaker, it is necessary to first close the open disconnected and then open the other disconnected. Since disconnections have no breaking or making capacity, it is essential that the bus bars are paralleled via at least one of the bus couplers.

There are many possible ways to achieve this. For example bus coupler C1 could be used when switching GTG GA from bus A.1 to bus A.2. It is also possible to use bus coupler C2, but in this case, all bus-tie circuits T1–T4 must be closed, meaning the four breakers and eight disconnections.

When switching GTG GB between bus bars B.1 and B.2, it is necessary to use either C1 or C2 or both, meaning that the associated bus-tie circuits must be also be closed.

Not only must the GIS be in the right configuration to allow the load transfer to take place, it must remain in this configuration until the transfer has finished. This takes time since the disconnectors are motor operated and are actuated one after the other. One consequence of this is that protection functions associated with the bus-couplers or bus-tie circuits are to be disabled during the transfer. Opening any breaker required to be closed during the transfer could cause a failure of the disconnected.

Although bus bar faults are very rare within GIS, project specifications may require bus bar differential protection. If this is the case, it is necessary to inhibit the bus bar protection of all the individual bus sections associated with the load transfer before initiating the transfer. The only bus bar protection left for these bus sections would be the check-zone, which encloses the complete GIS and its operation would result in tripping all of these bus sections. This could easily mean losing the complete switchgear lineup.

Due to all the possible configurations of the switching devices, a PLC was used. The PLC was installed within the 36-kV GIS (Fig. 13) and is an integral part of the switchgear. The only interface to other control systems is a potential free contact that indicates that it is healthy. Loads can also be transferred by first opening the closed disconnected and then closing the other disconnected. This operation is much simpler and easier to control but requires opening the circuit breaker first, thereby disconnecting the load or GTG.
That option is often refused due to the related production loss that could occur.
This example demonstrates that safe operation of switchgear can require complex interlocking that takes into account the status of all of the switches. Since the integrity of the switchgear is endangered by incorrect operation, it is recommended that the logic be implemented within the switchgear itself. One advantage of this is that the design is the responsibility of the switchgear supplier who knows best what is required. The other advantage is that this interlocking system can be fully tested during the FAT. This reduces the possibility of incorrect operation due to faulty logic or mistakes in connections at site should this system be installed outside the switchgear. It also reduces the commissioning time at site since all functions have been proofed prior to installation.

Fig. 13. Integration of control logic within 36-kV GIS.

C. Short-Circuit Current Limitation

There is another situation that can occur where excessive short-circuit current can result. This is due to the desire to have maximum flexibility in the power generation switchgear to avoid single-mode failures. Increased flexibility often means possible configurations where the short-circuit rating of the switchgear can be exceeded.

Fig. 14 shows nine GTGs that are connected to the utility through three step-up transformers.

The switchgear rating is 12 kV and 50 kA and operated at 11 kV with both bus tie circuits open. The short-circuit rating of the switchgear is sufficient to allow only three GTGs to be connected in parallel through the transformer to the utility. The rating is exceeded if there are four GTGs in parallel at the 11-kV level. As in the previous example, the interlocking to prevent the paralleling of more than three GTGs on the same 11-kV bus should be done within the switchgear itself and tested during the FAT.

Since the interlocking will prevent the closing of a generator breaker, the switchgear interlocking system should also have potential free contacts that can be used by the GTG control systems. There is no point starting a GTG if it will not be possible to close its breaker.

In addition to ensuring the integrity of the switchgear, care should also be taken regarding switching of the breakers to minimize the mechanical stresses seen by the GTGs. If it is necessary to be able to black start the system, the 11-kV transformer breaker should first be closed before starting any GTGs. The first GTG to be started should have its generator breaker closed in order to energize the transformer as it runs up to speed. This will avoid the large inrush current that would flow should one GTG be first run up to speed and then its breaker or the transformer breaker closed.

Opening a generator breaker when the GTG is heavily loaded will result in immediate acceleration of the machine. Although the machine is designed to withstand this, it is best to avoid it when possible. Opening a generator breaker or transformer breaker should be done by the power management system after first requesting the reloading of the GTG(s) to be disconnected.

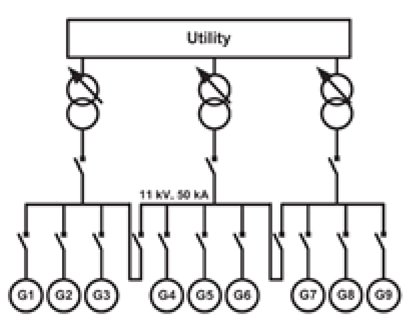

Fig. 14. Power station switchgear.

The actual trip order should be given by the GTG itself. To avoid accidental tripping by switching off a breaker at the switchgear itself, emergency stop buttons should be used so that tripping a breaker is allowed only in emergencies. The normal "off" button on the switchgear should be operational only in the test position.

Minimizing the mechanical stresses seen by the GTGs is not a design requirement for switchgear; thus, the switching procedures described above would be implemented in a different control system. Close collaboration between the GTG, switchgear, and control system vendors is necessary in order to ensure that each system is designed to take into account the requirements of the complete system and not just of the individual subsystems. Complete system testing would most likely be possible only at site, but it is recommended to do partial system testing during the individual FATs. This requires close coordination. The responsibility of the overall design including system testing should be clearly identified at the start of the project.

C. *Interlocking in FCL Application*

This final example shows what happens when all operating conditions are not considered during the design of the power system. It is an FPSO with GTG topsides supplying process power and diesel generators (EDGs) providing essential and emergency power. An FCL is installed in the 11-kV bus tie to limit fault current to an acceptable value.
During commissioning, it was discovered that there is one operating condition in which the short-circuit rating of the switchgear would be exceeded, even with the FCL in service.
This configuration is shown in Fig. 15 and happens when the GTGs in service are all on the same 11 kV bus, and all EDGs are in service and connected to a single bus by means of a closed bus tie. The combined contribution from the three GTGs and the three EDGs exceeds the 11-kV switchgear short-circuit rating of 50 kA should the fault occur on a feeder as shown.

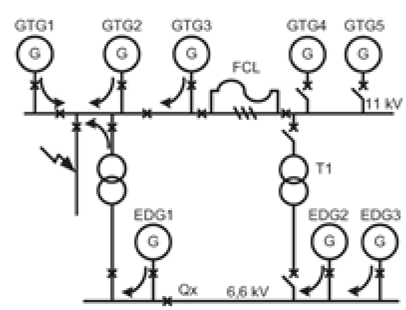

Fig. 15. Excessive short-circuit current.

Since this configuration was discovered at site, the only solution that could be implemented was additional hard-wired interlocking. The interlocking is quite simple and consists of immediately tripping breaker Qx should the configuration shown actually occur. It would have been much better to design the control system to prevent closing Qx or alternatively inhibit starting and connection of a GTG or EDG that would result in this operating configuration than tripping when it has occurred.

Due to the split between the switchgear control system and the GTG/EDG control systems, this was not feasible (1)

6 CONCLUSION

The FCL devices are an effective and reliable tool for system protection. Yet, a successful application is often dependent on characteristics of these devices that the system engineer may not be familiar with. This paper has discussed the importance of information gathering. The manufacturers of the FCLs are not only a source of application guidance but can predict the performance to help ensure that the needs are met. They are also a guide around potential pitfalls in the usage of these devices.

A robust design requires deep understanding of the equipment that is used and how it is integrated into the complete system. Robustness is enhanced by implementing the control functions as close to the equipment as possible. These control functions should be thoroughly tested at the equipment and system FATs. The test requirements should be defined during the design phase since meeting these requirements will ensure that the system has been designed accordingly.

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