Recent Trends and Innovations in Arc Flash Assessment

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RECENT TRENDS AND INNOVATIONS IN ARC FLASH ASSESSMENT

New equipment and innovations are marking improvements in arc flash systems and give a safer work environment for the staff involved in maintenance of the electrical equipment. Also some old established methods are being revisited. Coordination of instantaneous devices in series is a new field, as well as the development of current limiting low voltage molded case circuit breakers. There are also innovations in the construction of low – voltage MCCs, new breed of low - voltage trip programmers, remote racking of MCC buckets etc.

ARC FLASH STATISTICAL DATA

Statistical information of the arc flash hazard is presented in Figure 1. This figure shows the number of buses at various voltage levels in the electrical distribution systems. Majority of buses, 84.7%, are at low voltage levels. Figure 2 presents the buses' arc flash energy, for instance, it indicates that 5% of the total buses have hazardous incident energy level of 40–100 cal/cm^2 and on 1% of the buses the incident energy surpasses 100 cal/cm^2. Table 1 displays annual exposure for each equipment type. This table indicates that the annual exposure on low voltage MCCs is 365, on other low voltage devices 52, and on low voltage switchgear 12. The complete yearly exposures are 459, out of which 429 are on the low voltage devices, that is, 93.4%. The exposure on low voltage MCCs alone is 79.5%. This is in line with the industry development, which is focused on low voltage devices. In the design stage, by simply decreasing the ratings of low voltage transformers, short- circuit levels can be decreased, which in turn affects the incident energy levels.

Table 1. Yearly arc flash exposures for different devices and voltage levels

Device	Yearly arc flash exposures
HV(>34 kV)	2
MV (1-34 kV)	4
MV MCCs	24
LV Switchgear	12
LV MCCs	365
Other LV equipment	52

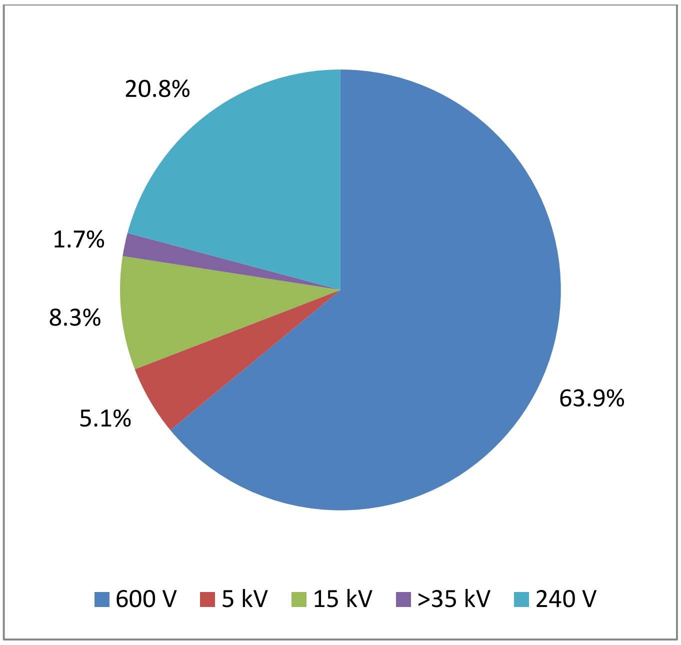


Figure 1. Statistical information of arc flash hazard with respect to different voltage levels in industrial electrical networks

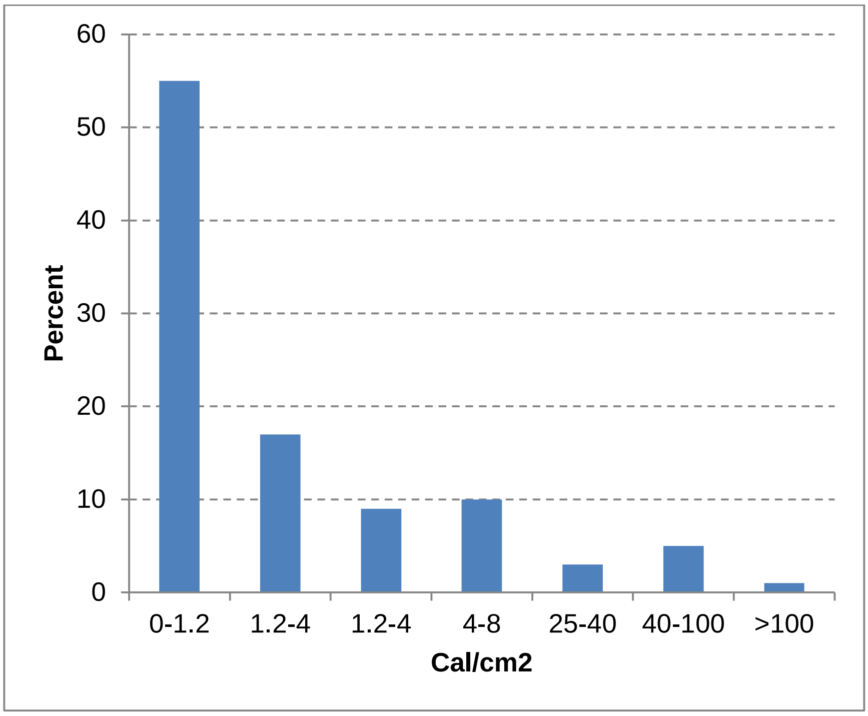


Figure 2. Incident energy release verses percentage of buses

ZONE-SELECTIVE INTERLOCKING ARRANGEMENTS

Zone - selective interlocking (ZSI) is an old concept revisited for arc flash mitigation. It can also be used for medium voltage electrical systems and maintain the selective coordination between main, tie and feeder circuit breakers allowing fast operation between equipment desired zones. This is accomplished through wired connections between trip elements and protection relays. If a feeder discovers a fault, it sends a restraint signal to the main circuit breaker, but for a short circuit on the bus, the main circuit breaker does not receive a downstream restraint signal and operates without any delay. The restraint logic is not instantaneous, and there is certain time delay related with it, so that there is no unrestrained tripping of the main. For security, a delay of 20ms can be used, although it is different from manufacturer to manufacturer. Typically, attention has to be paid to motor loads. A motor load will increase the bus fault current, and the feeder circuit breaker should not emit a restraint signal upstream when the motor contribution short circuit current goes through it. There can be multiple sources of power to a bus, and when several sources feed into a fault location, the zone interlocking system will be challenging to use, and differential protection can be used.

LOW VOLTAGE ZSI ARRANGEMENTS

Common low voltage distribution from a substation transformer is presented in Figure 3. The feeder circuit breakers and main circuit breaker use ZSI scheme.

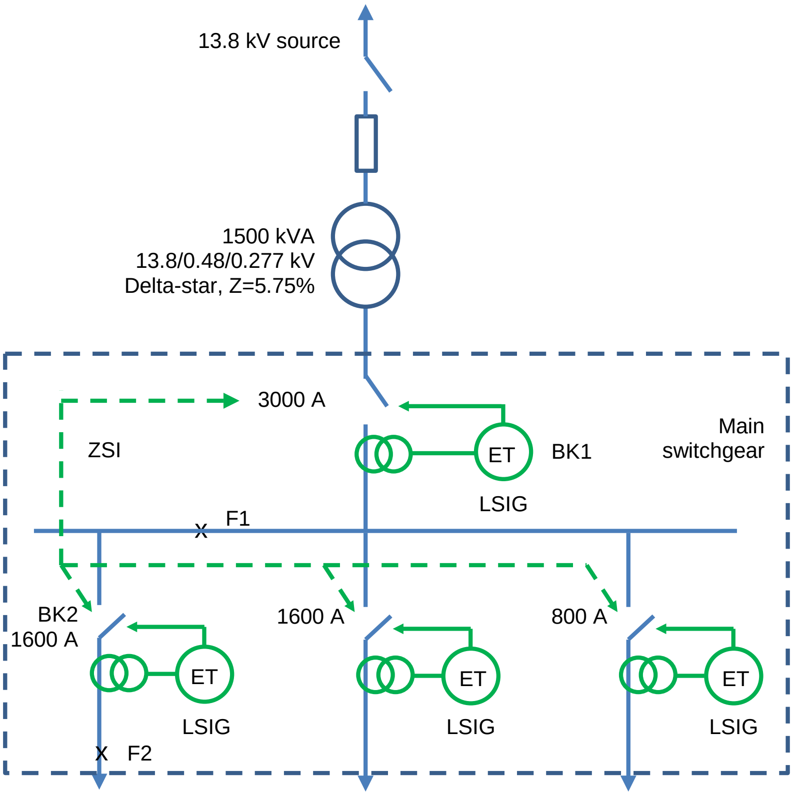


Figure 3. Zone interlocking scheme between feeder and main secondary circuit breaker of a low voltage transformer

For a fault at location F_1, the main circuit breaker does not get a restraint signal, and it operates with no intentional delay. For a fault at location F_2, the main circuit breaker gets a blocking signal and operates on short-time delay, allowing the feeder circuit breaker to first break the short circuit current. Figure 4 presents yet another arrangement.

Consider that the current sensors (CTs) linked to 50/51 protection relay R1 are installed in the transformer secondary terminal enclosure, and the protection relay itself is installed on the low-voltage switchgear. For a short circuit on the load side of the feeder circuit breaker F_2, it emits a signal to protection relay R1, and the standard settings can be used for coordination. For a short circuit fault at location F1, there is no ZSI signal, and the R1 uses a definite time delay, which is way faster than the delay necessary for coordination. It can be concluded that a coordination step between two elements in series is much decreased, reducing the arc flash hazard.

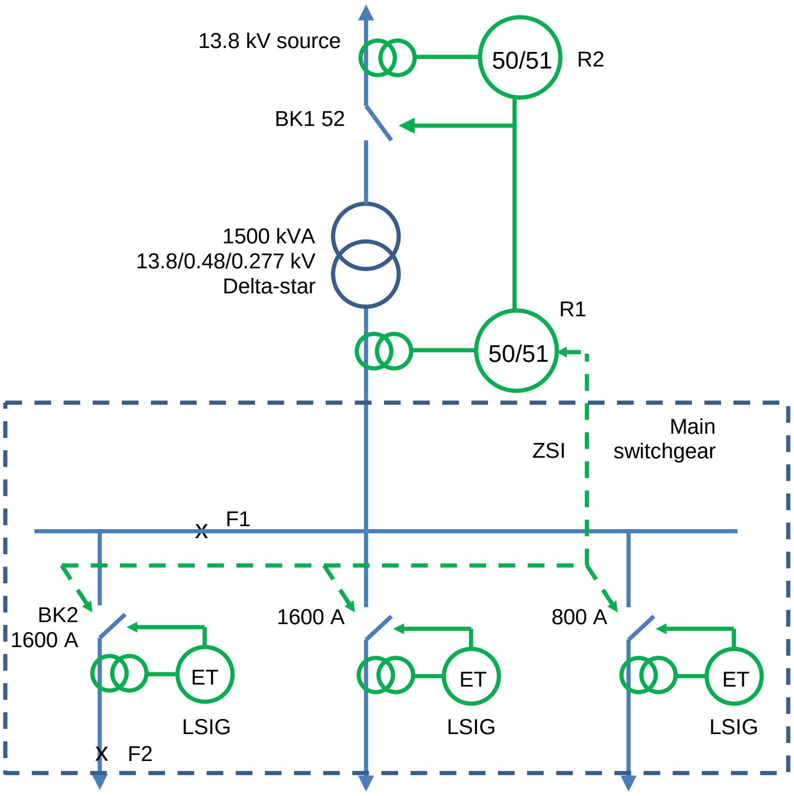


Figure 4. Zone interlocking mechanism between feeder and main secondary circuit breaker and also primary breaker of a low voltage transformer

EXAMPLE 1

Figure 5 presents a part of a distribution system from a 1500-kVA substation transformer. The main circuit breaker BK1 and feeder circuit breakers BK2 are zone interlocked. Figure 6 presents three-step coordination. The 400-A circuit breaker BK3 supplying the panel is a current limiting circuit breaker. Circuit breakers BK1 and BK2 are LVPCBs using electronic trip programmers.

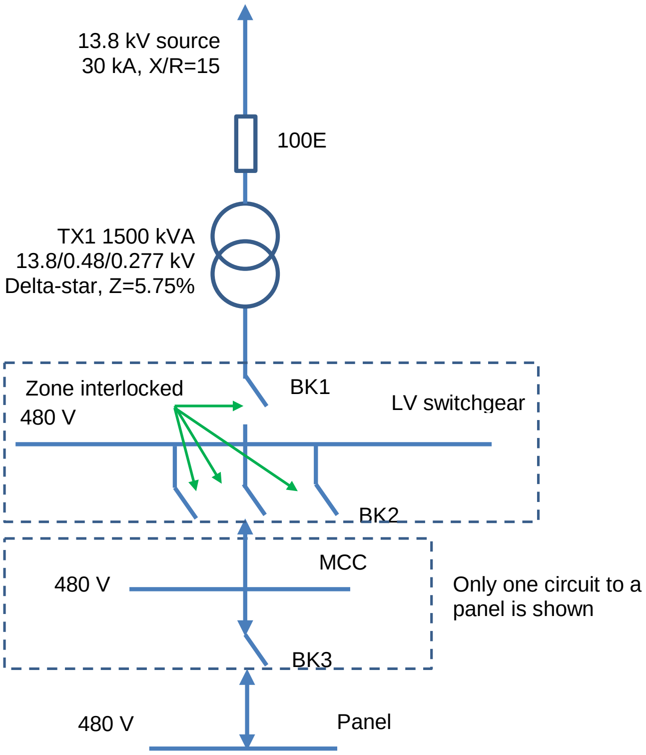


Figure 5. A low voltage electrical distribution system for zone interlocking assessment

The coordination presented in Figure 6 displays the zone interlocking options. For a bus short circuit, no signal to block the trip is got from feeder circuit breakers BK2, and circuit breaker BK1 removes the short circuit with its short-time delay band. In coordination, conservative steps are taken, and the short-time band maximum clearing time is considered. For a fault on the downstream of circuit breakers BK2, the main circuit breaker BK1 does not get any restraint signal and the normal coordination is applicable. That means the characteristic remains where it is. Therefore the feeder circuit breaker selectively removes the fault. With zone interlocking, the incident energy release is considerably reduced. In Figure 6, it looks that there is no coordination between the instantaneous characteristics of circuit breaker BK2 and BK3. Nevertheless, circuit breaker BK3 is a current-limiting circuit breaker, and the coordination on instantaneous basis can be achieved. Even though these two circuit breakers do not seem to coordinate in the TCC plot, on a current let -through basis, these breakers do coordinate.

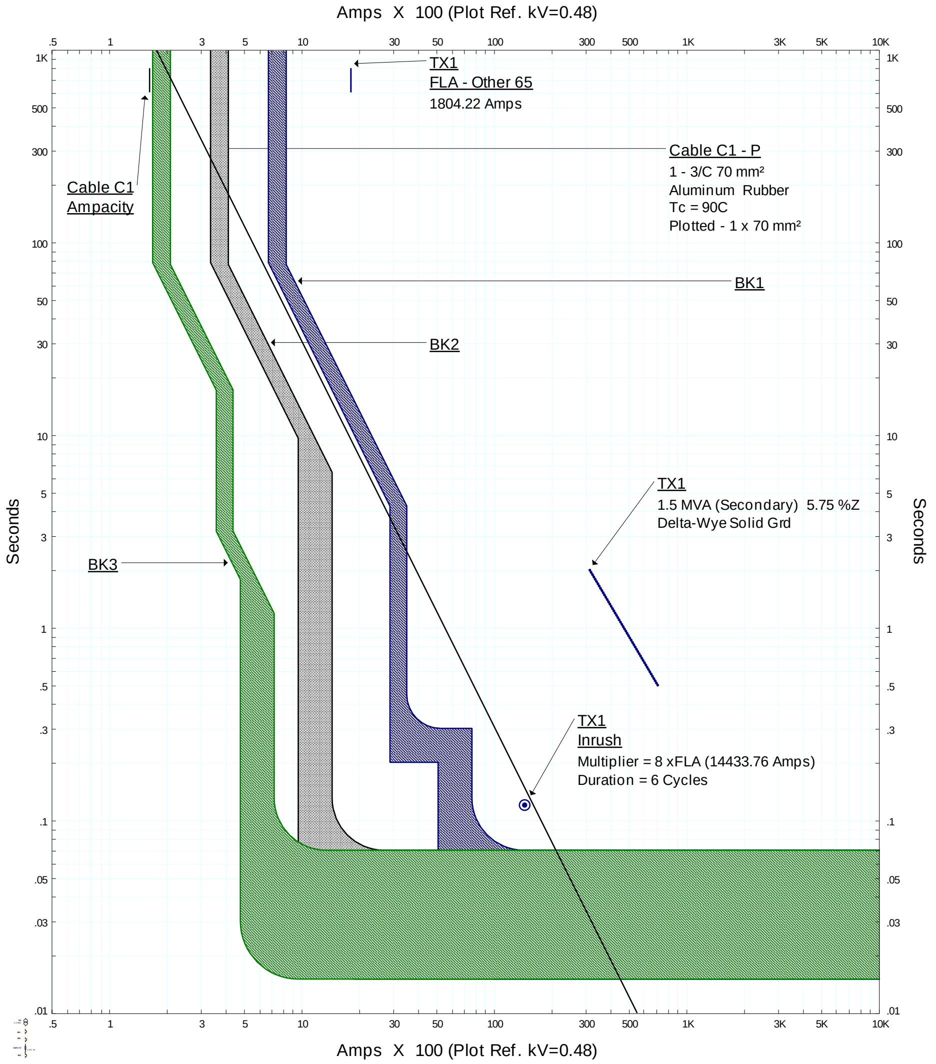


Figure 6. Time–current coordination of devices in Figure 5

EXAMPLE 2

The second example presents the problem that can happen with zone interlocking when big motor loads are used. Consider the system arrangement presented in Figure 7. The coordination is presented in Figure 8. The 200-HP motor starting curve is included. Also, a curve presenting the starting load plus the running load of 100-HP motor is presented. Potentially, the fault current profile of the motor loads could cross the feeder fault setting band.

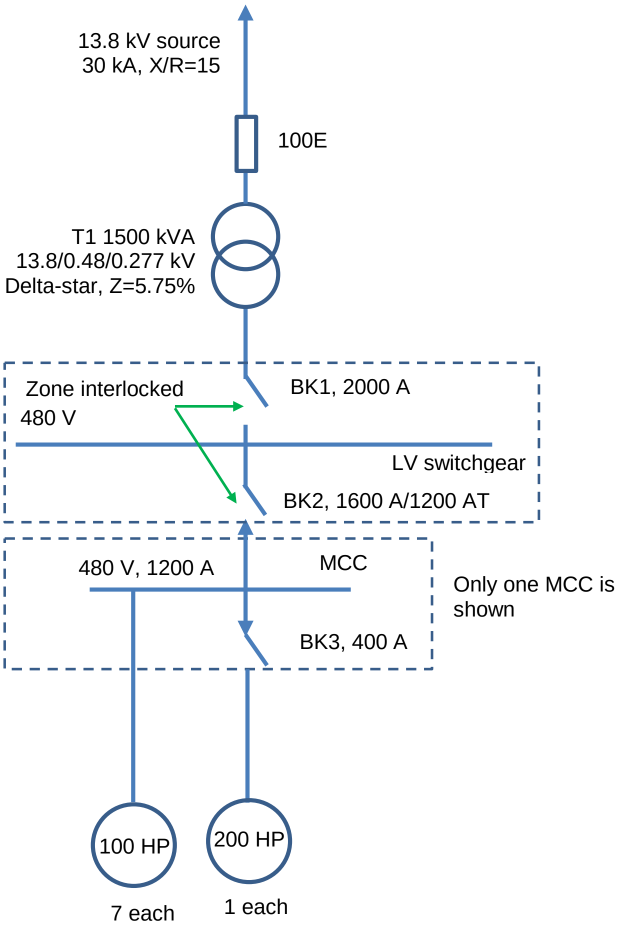


Figure 7. A low voltage electrical distribution system, with major rotating motor loads downstream for assessment of zone interlocking

This could lead to operating the feeder circuit breaker BK2. There are two potential solutions to this problem:

1. The fault band of the feeder circuit breaker relay can be increased so that it clears the motor fault decrement curve. This implies that the incident energy release and arc flash hazard will also increase.
2. The second approach uses the microprocessor-based technology to detect the short-circuit direction.

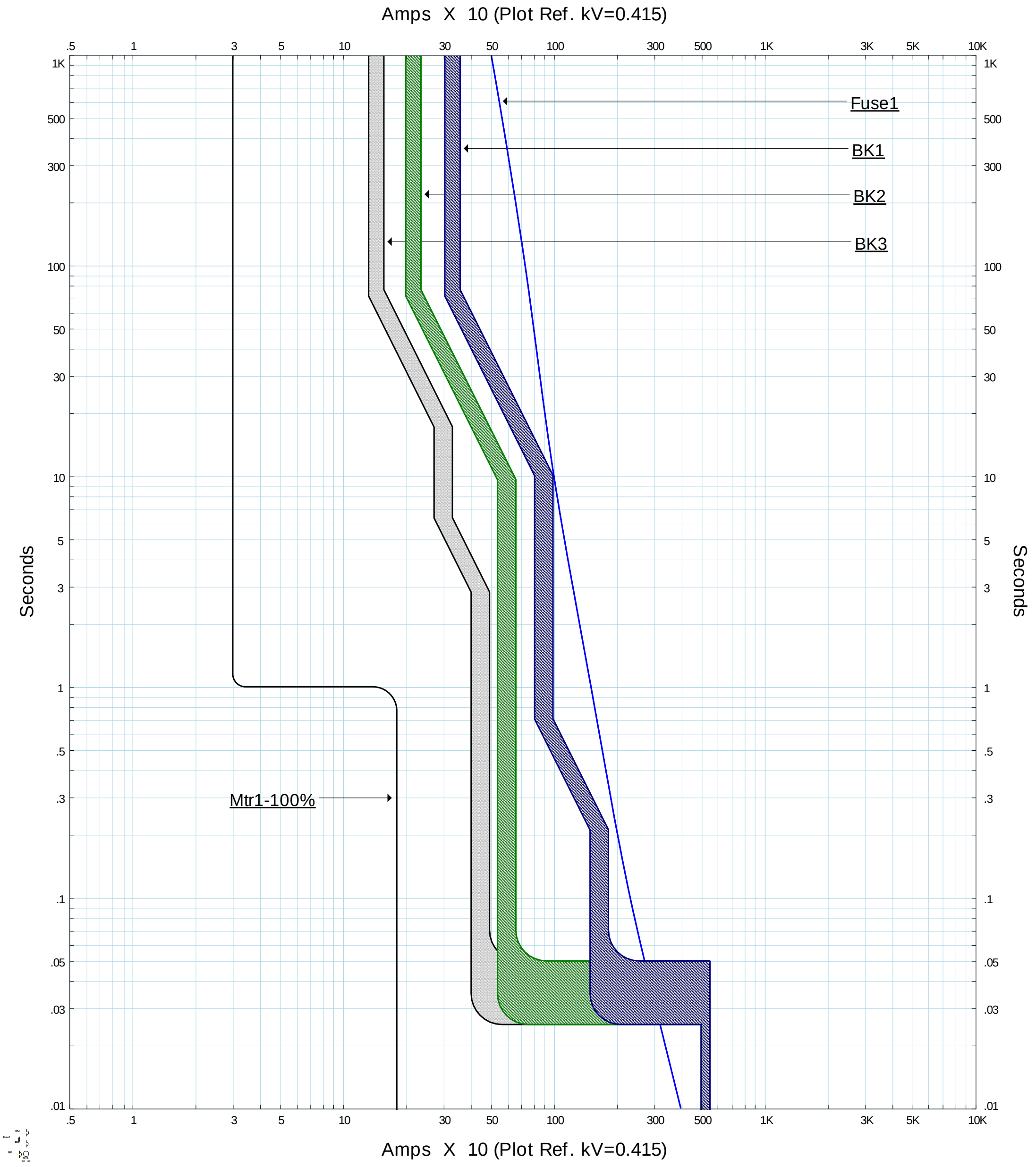


Figure 8. Time–current coordination of elements in Figure 7, presenting motor contribution that affects the settings

ZONE INTERLOCKING IN MEDIUM VOLTAGE ELECTRICAL SYSTEMS

Similar methodology can also be used for zone interlocking in medium voltage electrical systems. Figure 9 presents one such arrangement. Here, the MMPR protection relays presented as *R* have the adaptability to get a signal from the downstream protection relay, when the fault is downstream. Hard-wired or fiber optic communication channels can be applied. The upstream protection relay can bring altogether new adjustments or block a particular setting for a downstream short circuit.

This can be accomplished through the programming capability of these protection relays and Boolean algebra. Using adequate logic, it is possible to change settings or block settings depending upon the fault locations. In Figure 9, with two power sources and a bus section switch, the following operation must be ensured under different operating conditions.

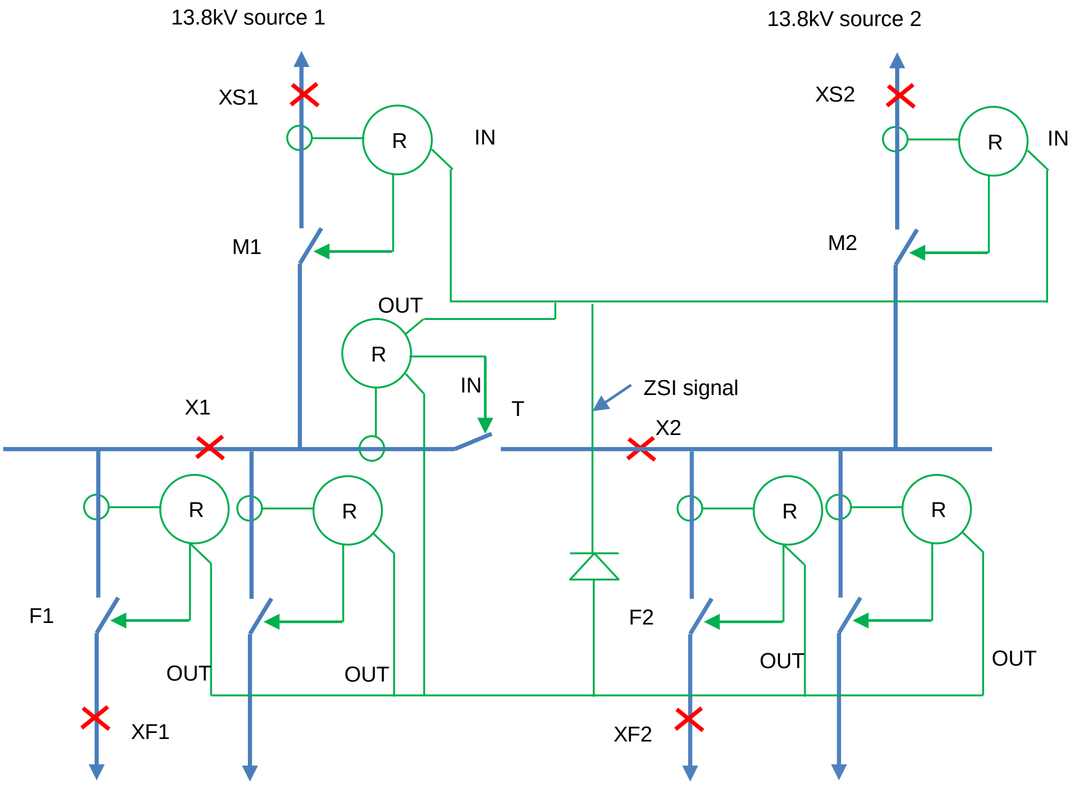


Figure 9. Zone interlocking in medium voltage electrical system with two power sources and bus section circuit breaker using microprocessor relays

BUS SECTION CIRCUIT BREAKER T OPEN, CIRCUIT BREAKERS M1 AND M2 CLOSED

- Protection relay on feeder F1 discovers the faults XF1. It emits a zone interlocking signal to protection relay on M1, and this will block operation of M1 unless coordination protection times are surpassed. This does not affect the tie circuit breaker since it is open.
- Similar operation happens for a fault at location XF2.
- For the short circuit at location X1, the short circuit is ignored by feeder protection relay, and no zone interlocking signal is transferred to M1. The protection relay at M1 will operate instantaneously, limiting the fault damage.

- Similar operation is accomplished for a fault at location X2.
- Faults at points XS1 and XS2 must be removed by upstream protection relays.

BUS COUPLER CIRCUIT BREAKER T CLOSED, CIRCUIT BREAKERS M1 M2 CLOSED

- A short circuit at location XF1 is supplied from both the sources. Protection relay at location F1 emits restrain signal to protection relay at M1, bus section circuit breaker T, and also to M2. Also, protection relay at bus tie breaker sends restraint signal to M1 and M2. The short circuit at location F1 is hence cleared by the settings on protection relay at feeder circuit breaker F1. Circuit breakers M1, M2, and T are blocked with the restraint signals.
- Similar operation happens for a fault at location XF2.
- Short circuit at location X1 is supplied from both the sources through M1, M2, and T. Now the bus section circuit breaker protection relay will send restraint signals to M1 and M2. The bus section circuit breaker T protection relay will operate instantaneously, as no restraint signal will be sent from the feeder circuit breaker protection relays. After the bus section circuit breaker is opened instantaneously by the operation of its protection relay, the relay at M1 operates instantaneously, as there is no restraint signal from the tie circuit breaker.
- Similar operation happens for a fault at location X2.
- The short circuit at source XS1 is supplied from the two sources, as the bus tie circuit breaker T is initially closed. Once the bus tie circuit breaker opens as described above, the short circuit will be ultimately removed by the source 1 upstream protection relays. Hence, the power to bus 2 is not interrupted.
- Similar operation happens for a fault at location XS2.
- This presents selective operation and only the defected bus is isolated, maintaining service on the healthy section of the bus.

BUS TIE CIRCUIT BREAKER T CLOSED, M1 CLOSED AND M2 OPEN

- For a short circuit at location XF1, there is only one source through M1 supplying the fault. The feeder protection relay still restrains protection relays at M1, M2, and T. The restraining signal does not impact M2 as it is already open. The feeder protection relay F1 will instantaneously remove the short circuit.

- For a short circuit at location XF2, feeder protection relay restraints the relays at M1, M2, and T. The bus tie protection relay also restrains M1 and M2. The restraint signals do not affect M2 as it is already open. Therefore, feeder protection relay instantaneously removes the fault location XF2.
- For a short circuit at location X1, no restraint signal is sent to M1, and it instantaneously removes the short circuit.
- For a short circuit at location X2, protection relay at bus section circuit breaker provides restraint to M1 and M2. Again M2 is already open. The bus tie circuit breaker T will instantaneously operate.
- Short circuits at locations XS1 and XS2 must be removed by the upstream source protection relays. Similar operation happens when tie circuit breaker is closed, M2 is closed, and M1 is open.

This description presents the complexity of applying ZSI to double - ended substations. The ZSI can be used for phase as well as earth short circuits. Where the number of sources is more than two and there is more than one bus section or a switched tie circuit, differential protection is adequate.

LOW VOLTAGE SWITCHGEAR WITH MICROPROCESSOR

Low voltage power circuit breakers with CPU–based protection, monitoring, control, and diagnostic features, which replace discrete elements and hard wiring, are available. These give increased reliability and arc flash reduction. Synchronization between two CPUs is achieved through a hardwired sync clock, and the CPUs critical controls are given through in-built UPS systems. For arc fault mitigation, bus differential mechanism with zone-based overcurrent protection is applied. For work near the equipment, decreased energy let-through mode can be chosen through a remotely installed switch. This allows more sensitive protection settings to decrease the arc flash incident energy.

MICROPROCESSOR SWITCHGEAR CONCEPT

The microprocessor-based arrangement can control every circuit breaker in the installation and simulate real conditions at that moment. For instance, if it can be noted that a short circuit is downstream of a feeder circuit breaker, the source side circuit breaker can be blocked from operating. The mechanism is to control each circuit breaker with complete data about every type of current flow in the electrical system. Hence, the system knows the amplitude and exact location of a fault at every instant. The selectivity does not have to be sacrificed. A microprocessor collects all pertinent system data and is able to simultaneously process it for the complete switchgear line up. All the current and voltage data is synchronized and is available in one location. Calculations can be done using simultaneous data samples or RMS information calculated over time. Note that the differential current at a bus has to be calculated in a simple radial system. Data samples of the currents going through all the circuit breakers at a certain time can be taken. Correct polarity assignment allows a differential calculation to be done with every data sample and current amplitude.

For instance, Figure 10 shows data samples at an instant for the currents going through three circuit breakers. The calculations can be adjusted for anticipated processing and signal error. Using standard CTs adequate resolution to discover short circuit currents lower than the rating of the protected bus can be accomplished. This calculation has to be completed for a short duration of 1 – 1.5 cycles and confirms with high degree of certainty the amplitude and position of the fault current. Finally, the same hardware giving normal overcurrent, earth fault, and ZSI can provide differential protection. The differential protection range is limited to 10 times the rated current of any CT in the electrical system to avoid CTs saturation. For example, for a 4000 A bus, a short circuit current > 40 kA is needed before the differential protection is made inactive, and for 800A circuit breaker, the differential protection is inactive at 8.0 kA. These currents are sufficiently high to be picked up in the short-time pick up range of the low-voltage trip programmers. The differential protection is combined with short-time zone interlocking, giving an overall protection range from low short circuit currents to the maximum available short circuit currents.

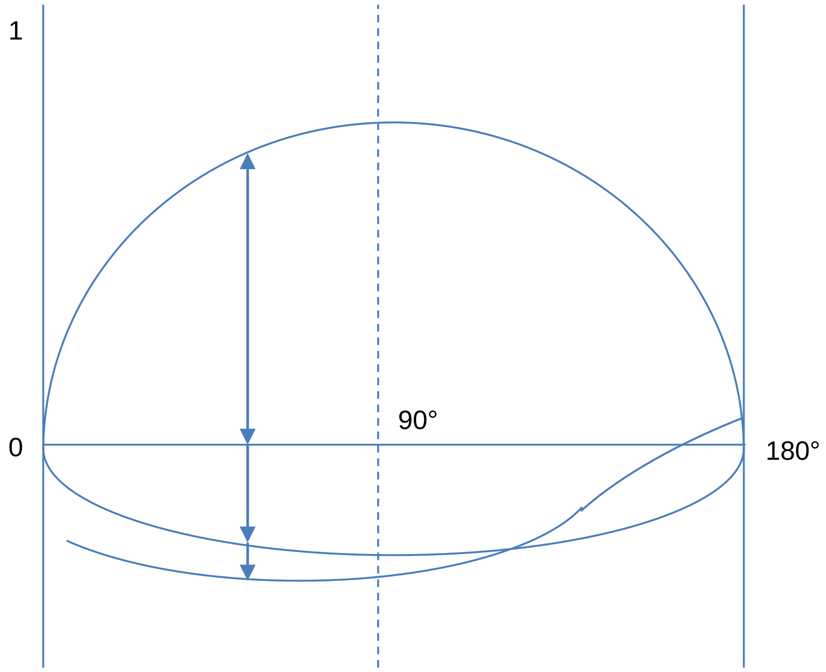
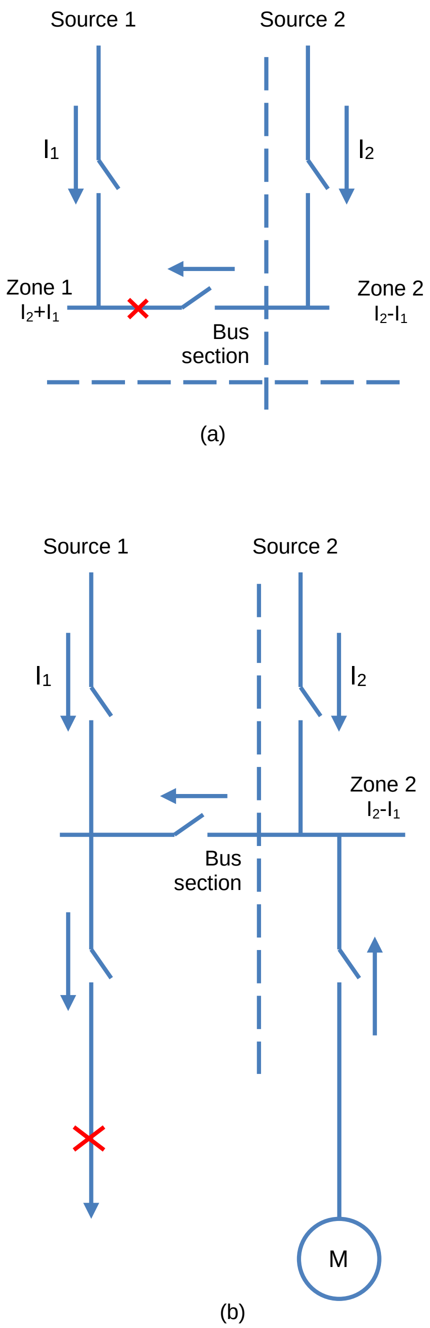


Figure 10. Instantaneous values of short -circuit wave forms from three source contributions found through instantaneous sampling

PROVISIONS FOR MOTOR CONTRIBUTIONS

If the ZSI is set to discover the fault current flow direction, an adequate operation with respect to motor contributions and multiple sources of short-circuit currents can be accomplished. The traditional zone interlocking arrangements do not discover short-circuit current direction, but with the microprocessor technology, it can be done. This is presented in Figure 11(a), which displays two source circuit breakers and a bus tie circuit breaker. An algorithm is made similar to the partial differential relaying. Partial differential computations are based upon the main and tie circuits, neglecting the feeders. Define a current direction as positive for the currents going into the bus and negative for the currents going out of the bus. Figure 11(a) indicates that the current flows for short-circuit on the left side, ignoring the feeder short-circuit currents. Two zones left and right are presented with dotted lines. For the left zone, the current runs from the two mains and tie are considered positive. For the right zone, the source 2 short-circuit current is positive and that flowing out of the tie is negative. Hence, it is discovered that the fault is on the left side of the bus. Now, analyze the fault on the feeder. Using the same convention, if the fault current goes toward the bus, say from a motor contribution, it is positive, and if it goes out from the bus to the feeder, it is negative. This discovers a feeder fault. The rotating motor loads on one feeder will feed into the bus, and consider that short-circuit is located on the second feeder as shown in Figure 11(b). In this situation, the current flow into the bus is positive from one feeder, and going out of the bus is negative from the other feeder, which discovers the fault position.



(a)

(b)

Figure 11. (a) Position of short-circuit through discovering the fault current direction (b) with motor loads.

The following formula can be written:

$$I_r = \sum_{1-p} I_m - \sum_{1-q} (I_t D_t) \qquad (1)$$

where:

I_r - the residual current for the partial differential zone

I_m - the current from the mains

I_t - the current from the tie

D_t - the reference direction unit vector for the tie

p, q - the numbers of mains and ties supplying the partial differential zone.

I_r is compared with the highest current in the system scaled up by a factor of 1.5. It may happen, that one or more current readings surpass by 10 times, than the short-time pickup has to selectively remove the fault. In this situation, it becomes necessary to find a large phasor, and all currents in the short-time pickup range are cross compared with this reference phasor to discover the relative direction. For each phase, a reference current and angle is determined. Following equation is used to determine if the other short circuit currents in the partial differential zone are in phase:

$$\Delta\theta = < I_\alpha - < I_\beta \qquad (2)$$

where $<I_\beta$ is the reference and $<I_\alpha$ is the phase angle of the considered current. For the opposing current, anticipated angular difference is of the order of 180°. Only feeder currents that are in the short-time pickup range are considered. A feeder current of 10 times will be above the motor short-circuit contribution, and is indicative of short-circuit downstream of the feeder. The feeder current is also cross compared to a reference phasor to discover its position. This allows that all circuit breakers in assembly are fast tripped, therefore decreasing the arc flash hazard.

SHORT CIRCUITS ON THE SOURCE SIDE

One more consideration has to be addressed before completing the picture. A short-circuit on the source itself will stay indeterminate, as neither of the sectionalized buses will indicate the fault position on them. An additional algorithm to discover the directions of the short circuit current through the main circuit breakers is needed. This is accomplished by analyzing the past data prior to the fault. Then a cross comparison can be done with pre-fault voltage to pre-and post-fault current. Observing the phase angle of the short circuit current with the phase angle of the pre-fault current can discover the reversal of current:

$$150° \leq \alpha_1 - \beta \leq 250°$$

where:

α_1 - the positive sequence current angle phasor

β - the pre-fault voltage positive sequence phasor

The angle for a forward current will be 0–90° for a purely resistive to purely reactive current. A current reversal will add 180° and would range from 180 to 270°. The pre-fault positive-frequency voltage phasor will demand compensation for any mismatch between sampling rate and frequency. The CTs can be installed on the source or load side of the circuit breakers. For differential protection, the installation of current sensors is vital. For incoming mains from the power transformers, the sensors can be installed on the source side of the circuit breaker cubical.

ARC FLASH HAZARD REDUCTION

With the previously described algorithms, the detection time is around 25ms while keeping selectivity. The energy let-through from a fault is greatly decreased. Faster diagnostics, troubleshooting and redundancy of two synchronized microprocessor give additional reliability. The system scheme is presented in Figure 12.

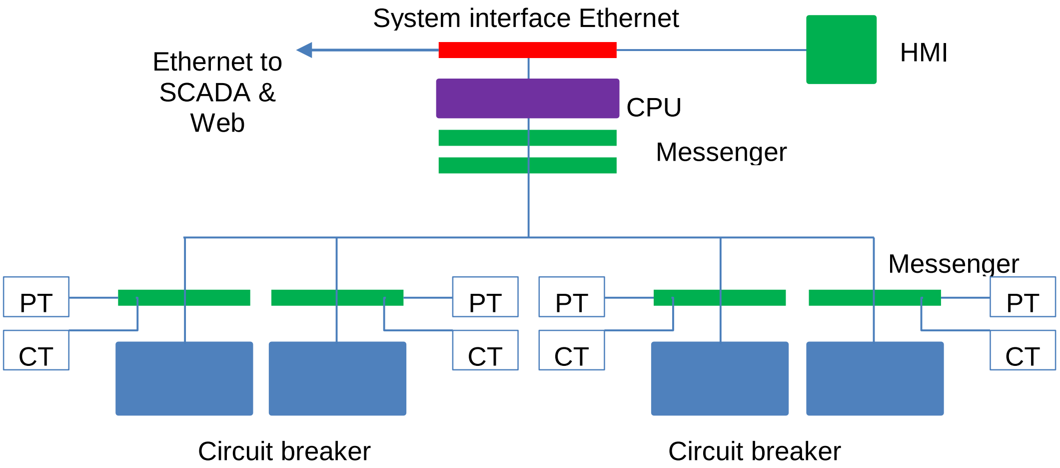


Figure 12. Microprocessor low voltage switchgear scheme

LOW VOLTAGE MOTOR CONTROL CENTERS

Table 1 indicates that 79.5% arc flash exposure happens on the low voltage motor control centers (MCCs). Process industries are dependent mainly on low-voltage MCCs. Typically, a shutdown of an MCC can result in shutdown of a large part of the processes. Therefore, the maintenance staff is faced with the task of troubleshooting or testing when the MCC is energized. The doors in MCC cabinets are interlocked to prevent access to energized devices with the disconnect element in the “ON” status. An interlock bypass system is provided for the qualified staff to access the live elements. Therefore, maintenance work is done with the door open in the energized state. The MCC bucket installations with plug-in-stab contacts can be withdrawn with the door open and MCC energized.

Removal of the MCC bucket is typically followed with a bench test. Unless attention is paid during handling the drawn-out bucket, and while work is being done, an undesirable force on the stab fingers can distort them. This can end in misalignment on insertion and decreasing the reliability.

MCC DESIGN OPTIONS

The following are the MCCs desirable design options:

- Provide finger safe terminals throughout, preventing exposure to live elements
- Make sure that all joints have been sufficiently torqued at the factory installation
- Give voltage indication on the outside of the unit
- Equip insulation and isolation of bus with shutters
- Supplier needs to provide correct installation and maintenance instructions
- All elements have to be adequately rated
- Inadequate elements should be rejected during assembly or maintenance
- Testing of all voltage sources installed in the unit should be provided on the dead-front cover
- Provide facilities for remote racking
- Fuses and high current- limiting circuit breakers have to be used.

RECENT DESIGN ADVANCES

Suppliers are continuously improving the designs for reliability and safety. Some of these advances include:

Remote Racking Capability and Safety Shutters – Similarly to medium voltage switchgear, the MCCs' buckets can be remotely drawn out. It contains unit stab assembly that allows this operation. Also, safety shutters will close the live spouts on draw-out. On the top of the unit is an assigned space for mechanical racking system through a motor operator. If a flash over happens, the operator will be outside the arc flash boundary.

Heavily Latched Doors - Arc flash hazard is more dangerous to a worker with the MCC door open. Even in MCCs not designed to meet arc resistant categories according to ANSI/IEEE standards, much improvements in securing and latching the MCC doors are used.

Door-Mounted Voltage Test Block - MCCs can be equipped with an externally installed voltage test block, accessible with door closed, to discover the presence of voltage before any tag-out procedure for maintenance. One indicator for the main bus and another on load side of disconnects can be used.

Main Current-Limiting Fuses or Circuit Breakers – Typically, the MCCs are equipped with main incoming cable lugs and no main circuit breakers or fuses. For a short circuit on the horizontal or vertical buses, and pull-apart MCC stab-on terminals, the protection is secured by an upstream circuit breaker in the low-voltage switchgear line. Provision of a main current-limiting element can provide faster clearing times and reduction of HRC. Nevertheless, it may be an issue to coordinate it with the downstream MCCBs and upstream circuit breaker. For a solidly earthed system, the line-to-earth current will be big, and the fuse operation in one faulted phase can give rise to single phasing and potential motor damage.

Improved Low Voltage Motor Protection - A new system of protective equipment is replacing the motor thermal overload elements. For example, a motor protection element can give the following functions:

- Metering and event recording
- Thermistor protection
- Under power, phase reversal, PT fuse failure
- Multiple of communication protocols
- Current unbalance
- RTD over-temperature
- Capability to accept zero-sequence CTs for sensitive earth fault protection
- Improved thermal modeling

For an induction motor with a locked rotor current of six times the full-load current, the negative sequence impedance is roughly one-sixth of the positive sequence impedance. A 5% negative sequence component in the supply system will generate 30% negative sequence current in the motor, which provides additional heating and losses. The rotor resistance will change according to high rotor frequency, and rotor losses are bigger than the stator losses. A 5% voltage unbalance may give rise to 30% negative sequence current with 50% increase in losses and 40°C bigger temperature rise in comparison to operation on a balanced voltage with zero negative sequence components. Also, the voltage unbalance is not same as the negative sequence component. The definition of percentage voltage unbalance suggests that it is maximum voltage deviation from the average voltage divided by the average voltage as a percentage. Operation above 5% unbalance is not advised. The bimetallic thermal relays, typically used for low voltage motor protection, are not sensitive to negative sequence and earth fault currents. Even though extensively used in the industry, these are a possible cause of motor winding damage.

Insulation and Isolation - The horizontal bus and the vertical bus are insulated. Shutters isolate the vertical bus when a unit is taken out and shutters on the unit isolate the stabs when the bucket is taken out. Finger-safe elements are given inside the units.

HIGHER SHORT -CIRCUIT WITHSTAND MCCS

The MCCs demand a three-cycle three-phase fault test on the horizontal and vertical buses for which these are rated, that is, 42, 65, or 100 kA rms symmetrical. Usually, these fault ratings may not be proper, as no main circuit breaker is provided on the MCC, and the MCC buses are protected with an upstream circuit breaker in the low - voltage switchgear installation. In case an instantaneous function is not given on the trip programmer of the circuit breaker supplying the MCC, the time duration of fault withstand can easily surpass three-cycle. Majority of low-voltage trip programmers have a lowest short-time band of 0.1 second (6 cycles).

MAINTENANCE MODE SWITCH

The maintenance mode switch is known by different names. Its usage in the maintenance mode activates alternate settings to decrease the arc flash hazard. These are being supplied on low voltage trip programmers and can be installed remotely. For instance, if a maintenance mode switch is supposed to decrease the arc flash risk on the MCC, it can be installed on the MCC itself, though it will actuate to bring the new settings on low voltage trip programmer installed on upstream circuit breaker, in the low voltage switchgear. Typical circuit that has maintenance mode switch wired in a MMPR is presented in Figure 20.

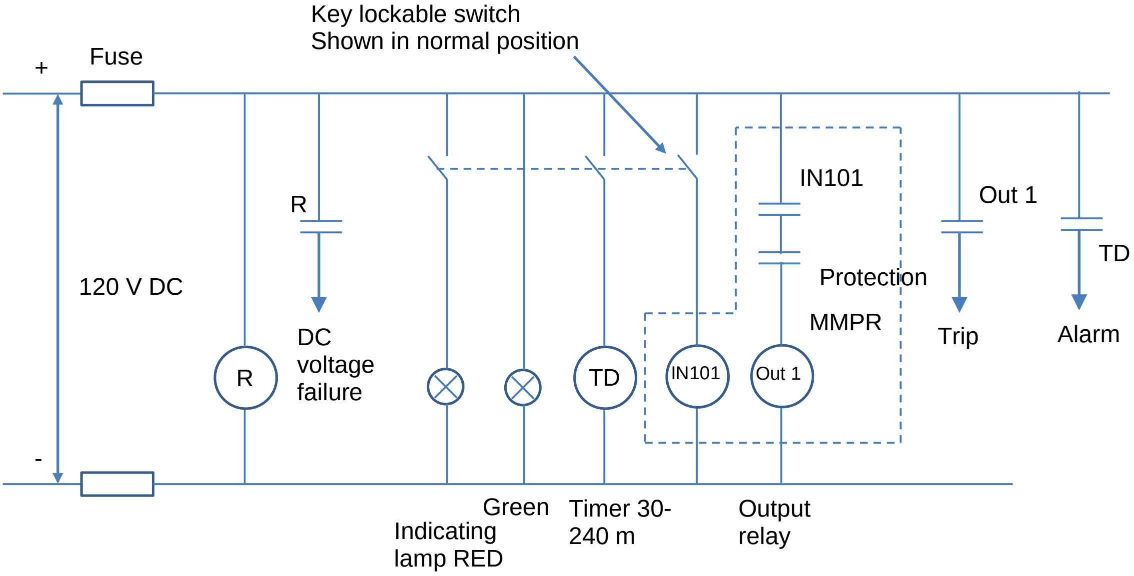


Figure 20. Connections of maintenance mode switch - control circuit diagram

The operation of the switch activates the input relay IN101, and an AND gate can be created with the desired protection setting, with output directed to “Out 1.” Typically, a timer circuit is excited, and the needed time for the maintenance process can be programmed on it. To stop unauthorized service, the switch can be key-interlocked. Moreover, it is possible to simultaneously control a number of such switches through a programmable device.

Despite all these safeguards, the following points are of interest:

- The selectivity is compromised in the maintenance mode. If a short circuit does happen, though the operator is protected, a bigger process area will be shutdown. This may require increased time and manpower to restore the operation resulting in revenue loss.
- Even is situations coordination is partly sacrificed, it should be possible to carry out the normal running loads or start a motor. This demands that a precise coordination study is done and it brings about the issue of reliability — that the alternate adjustments are not grossly lower or inadequate to sustain even the load operations.
- A person attending to energized device has to be prepared for a trip and its resulting consequences, even though the chances are small.
- Attention has to be exercised that the adequate maintenance mode switch is activated. This demands clear labeling and operating instructions.
- It is clear that two sets of arc flash calculations have to be done, one with the maintenance mode switch and the other without it. A dilemma happens on how the equipment needs to be labeled for arc flash hazard. If the device is labeled with lower arc flash hazard with the maintenance mode switch, it has to be part of the maintenance procedures that the equipment is labeled.
- Returning the maintenance mode or arc flash reduction switch to its typical position can be neglected. In Figure 20, one contact on the maintenance mode switch energizes a timer, which can be set by the operator for the intended maintenance duration. If the switch is not brought back to the normal position after the setting on the timer is surpassed, an alarm can be sounded. This introduces an extra step in the staff training.

Despite these points, arc flash reduction and maintenance mode switches are used in many industrial applications. These are an economical means to decrease the arc flash risk. It is possible to design a completely coordinated systems, which also decreases the arc flash, but at considerably bigger cost. This may involve installation of different protective devices, for instance, differential and unit protection systems. Typically, this is difficult to implement in an existing distribution system.

INFRARED WINDOWS AND SIGHT GLASSES

Infrared scans are sophisticated diagnostic methods and are done with the equipment energized. It can find high resistance connections or “hot spots”. The assessments are done with the equipment energized and when transferring normal load currents. It is a comparative test type in which the thermographer does a scan to find areas that appear brighter (hotter) in comparison with similar areas being scanned. Infrared camera cannot see through cabinet covers, and installations of infrared sight glasses are used. The construction of these windows and sight glasses does not expose the thermographer or the equipment at risk. The two distinct products are:

- Viewing windows: These are made to give accidental impact and only give visual inspection. These are not made for withstanding the internal pressure due to arcing, and provide no arc flash protection.
- IR ports typically have a mesh or grill and open hole that allow IR radiation to go through. They provide no protection in the case of an arc flash.
- The infrared inspection window include locking security covers and demand a trained staff to remove the covers before an IR scan. This is needed to protect the optic material from day-to-day impacts. The cover gives extra protection during arc flash.

The mandatory testing procedures suggest that the transparent covering of an observation opening must be secured in place so that it cannot be easily displaced in service and should comply with the following requirements:

- The viewing panes must not shatter or crack or become dislodged when both sides of the viewing pane in turn are tested.
- A force of 445 N (100 lb-ft) has be exerted in a plane perpendicular to the surface in which the viewing pane is installed. This force should be equally

distributed over an area of 16 in^2, and if the viewing pane is less than 16 in^2, the force has to be equally distributed over the viewing area and kept for 1 minute.

- The viewing pane is exposed to an impact of 3.4 J (2.5 lb-ft) using a steel ball weighing roughly 0.54 kg and measuring roughly 50 mm in diameter.
- If viewing pane is intended to be exposed to insulating oil in a tank, it needs to be made of material that is resistant to insulating oil.
- Category A equipment needs to have lockable covers over viewing panes, if viewing panes are provided. Category A cabinets are supposed to give protection against contact with enclosed equipment in ground level installations that are exposed to deliberate unauthorized acts by members of general public.

An IR sight glass, tested to be arc-resistant up to 40 kA arc flash current, with field of view equal to six times the cabinet depth is shown in Figure 22.

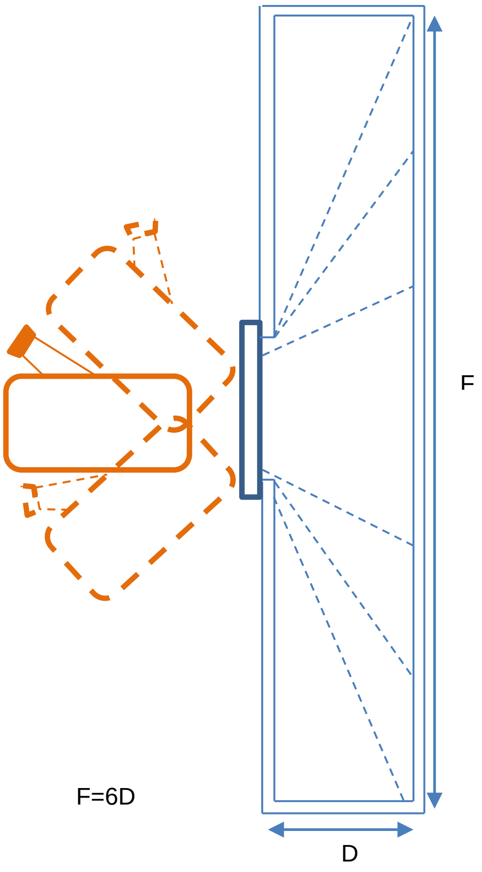


Figure 22. Infrared window field of view is equal to six times the cabinet depth

FAULT CURRENT LIMITERS

A fault current limiter (FCL) or triggered current limiter (TCL) limits the short circuit current in time and amplitude, operating in 1/4 to 1/2 cycles and providing no resistance to the load current flow. Figure 25 shows operational schematic diagram of FCL.

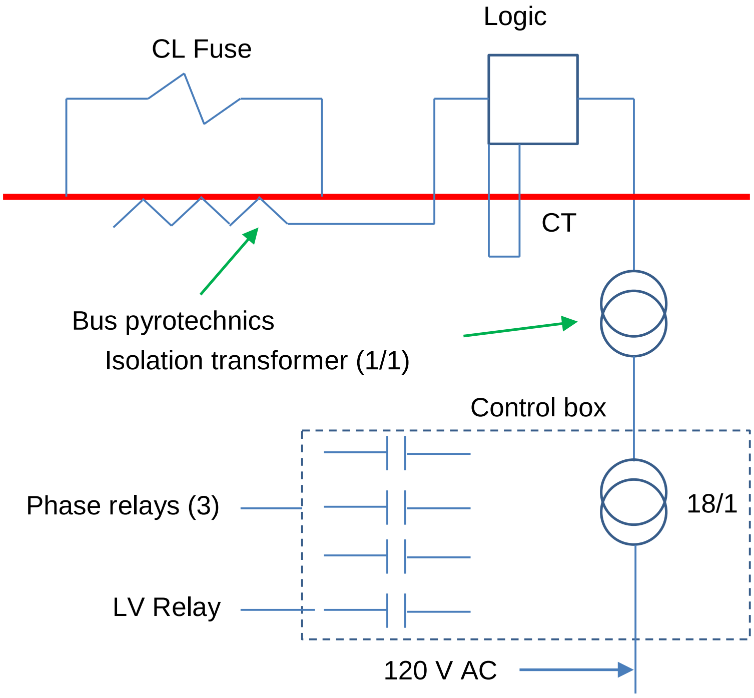


Figure 25. TCL schematic diagram

The main elements include firing and sensing logic, a large copper bar, an explosive charge, and a parallel current-limiting fuse. The firing and sensing logic element is linked to a current transformer on the copper bar installed ahead of parallel fuse. The copper bar transfers the load current under normal operation. Explosive material is used to pyrotechnically cut the bar on demand. The copper bar with explosive charge is usually enclosed in fiberglass enclosure. The current transformer and firing logic are installed on the bar and are at line potential. Optionally, the electronic measuring and tripping device may be remotely installed. The logic unit is linked to the external power supply and control the unit through the isolating transformer installed in the copper bar support insulator. The conductor is cut at high speed, usually around 5 mm/μs, while the gas pressure is used to fold the bridging member. The gaps created in the conductor are not sufficient to break the short circuit current, and the arcs created in these gaps create an arc voltage, which transfers the fault current into a parallel small cross-section fusible element. The current-limiting fuse works in the conventional way, providing current-limiting action. The overall breaking time is 1/4 to 1/2 cycles, before the prospective fault reaches its first peak. The adequate operation of TCL imposes a number of constraints on fusible element. It must not work on the fractional current that flows neither through it nor by the inrush and fault currents. Two detection modes are available:

- *di*/*dt* sensing
- Threshold sensing.

di/*dt* sensing determines the rate at which the current is rising, while threshold sensing simply responds to the current magnitudes. Timing diagram is presented in Figure 26.

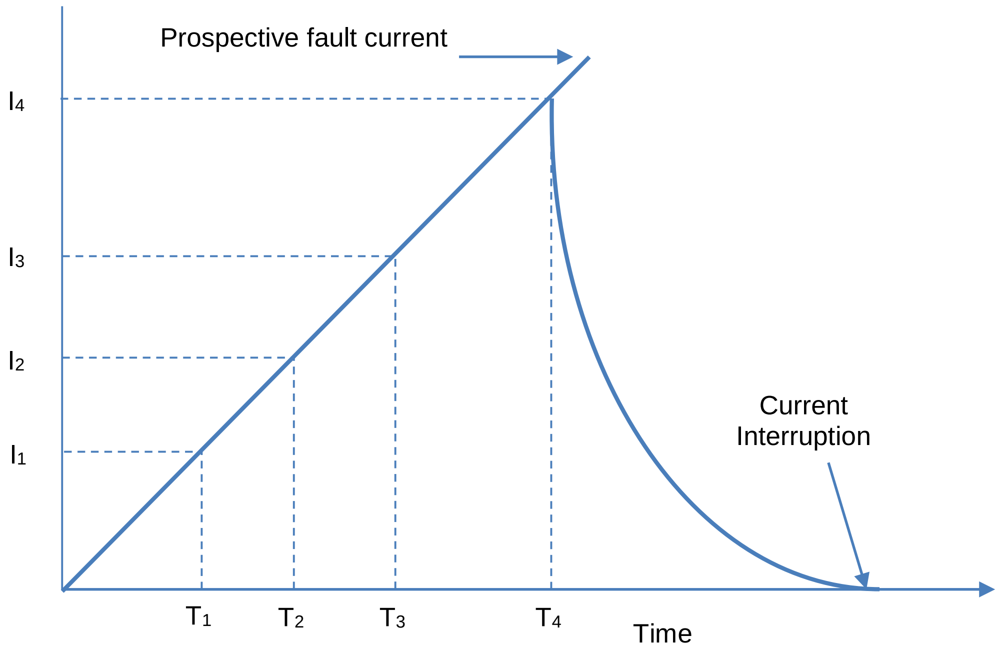


Figure 26. TCL timing diagram with magnitude sensing

- I_1 is the current sensing level equivalent to the trigger level
- T_1 is the sensing time delay
- I_2 is the current at trip initiation after a delay
- T_2-T_1 is the trip initiation delay
- I_3 is the current at commutation to parallel fuse
- T_3-T_2 is the commutation time delay to fuse in firing the pyrotechnics
- T_4-T_3 is the fuse melting time
- I_4 is the peak let-through current.

Due to a fast short circuit clearance, the energy let-though is decreased. Table 2 presents the energy let-through for a short circuit current of 40 kA, with different interrupting elements. Figure 27 shows that the post-fault voltage quickly recovers and that shutdowns due to short circuit voltage dips can even be prevented. The arc flash hazard will be decreased due to this fast operation.

Table 2. Comparison of I^2t of different current interrupting elements for 40-kA fault current

Device	I^2t
Five cycle breaker with two cycle relaying time (seven cycles, 60 Hz)	1.87×10^8 A^2s
Expulsion fuse operating in 1 cycle	2.67×10^7 A^2s
Current limiting fuse	10×10^5 A^2s
TCL	1.0×10^5 A^2s

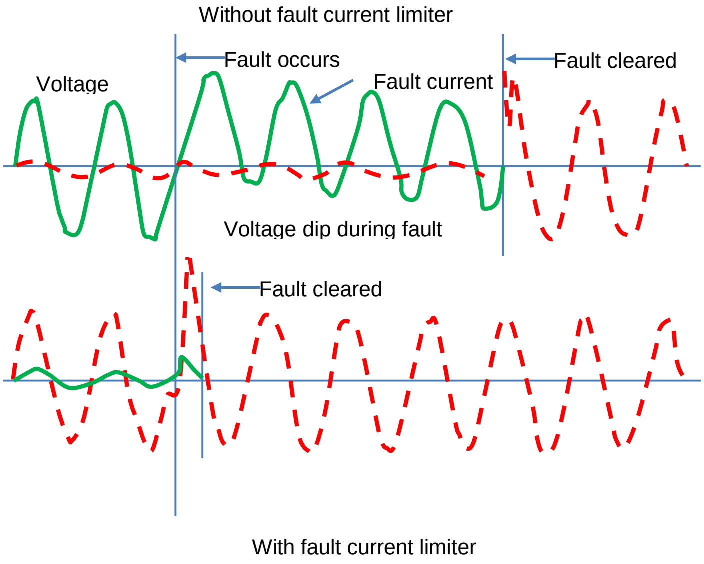


Figure 27. Controlling the system voltage dip with TCL

An application in a bypass reactor arrangement is presented in Figure 28 (a) and (b)

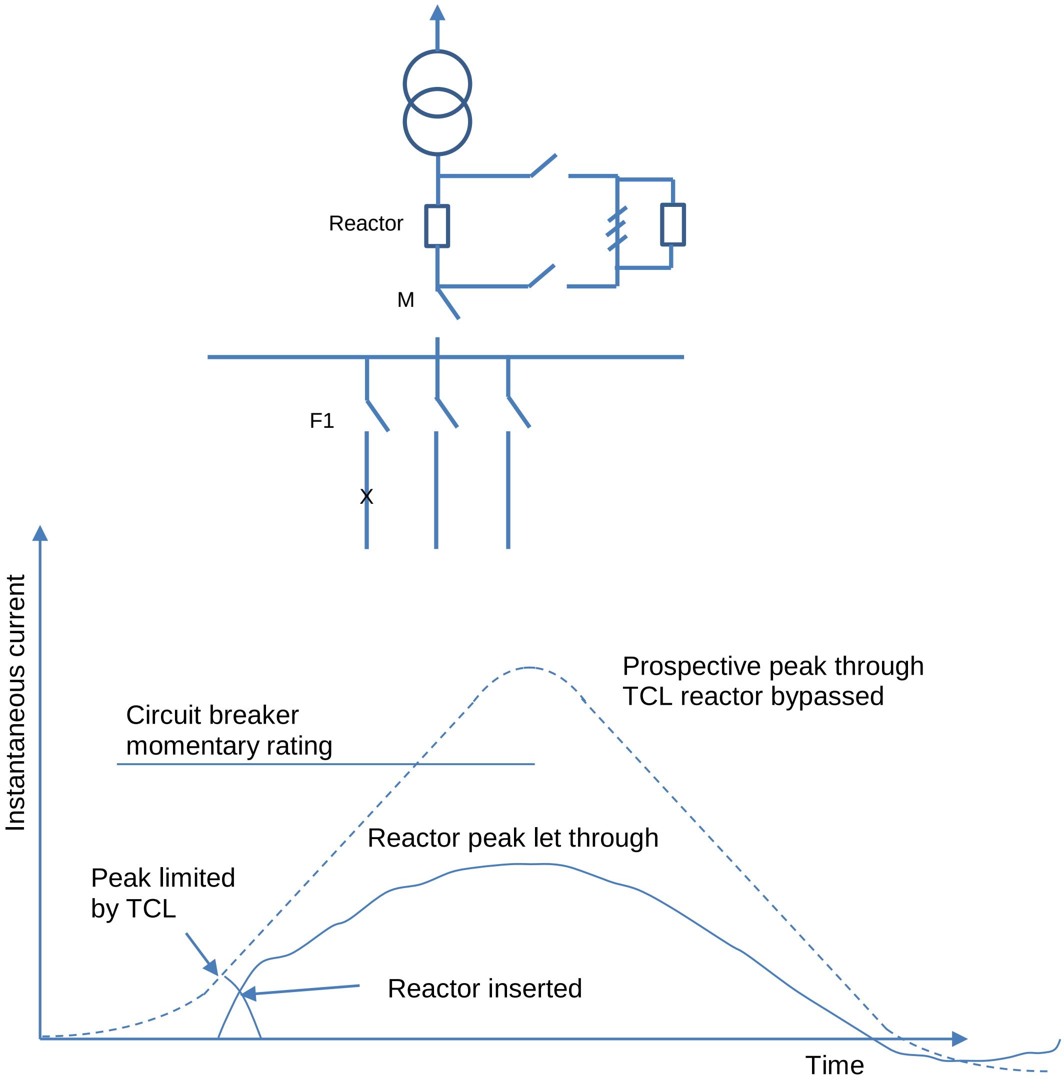


Figure 28. (a) TCL installed in a reactor bypass arrangement (b) time–current profile, peak limited by TCL, circuit breaker momentary rating, peak through reactor, and prospective peak current

Note that a reactor is used to limit the fault current on the 13.8 kV bus so that the existing switchgear can be kept in service. Nevertheless, the reactor has an adverse effect on the load flow and the voltage regulation. Then, typically, the reactor can be bypassed by the TCL, and the load flow situation improved. It is thought that the TCL works so fast that lower rated circuit breakers can be kept in service. Also imagine a downstream fault. The TCL can operate to introduce the reactor, which will limit the short-circuit current to acceptable level within the switchgear interrupting rating. This situation is presented in Figure 28(b). The following considerations are applicable:

- It is not always true that the existing circuit breakers with lower rating will not be exposed to higher first cycle or momentary ratings

- The short circuit current through TCL, feeder circuit breaker F1, and main circuit breaker M will be roughly same, if the short circuit happens close to the load side terminals of the feeder circuit breaker. The instantaneous overcurrent protection should not react until the reactor is introduced.
- The replacement costs of blown- out TCLs are considerable.
- The control supply arrangement for TCL must be duplicated with auto–changeover to provide reliability.

From the above arc flash considerations, unit protection arrangements, like differential relays and AFDs, are better choices. These work almost equally fast but within their protected zones. As far as other benefits claimed for TCLs of retaining underrated switchgear in service, a caution and detailed assessment is needed.

PARTIAL DISCHARGE TESTS

The partial discharge measurements methods have come a long way and are an efficient technique of evaluation of electrical insulation and avoidance of a forced shutdown. Industry statistics show that 80% of all failures of plant and equipment are random and only 20% are related to age. These indicate that 80% of prospective defects are not discovered by typical maintenance methods. Partial discharge measurement is widely accepted indicator for the failure of insulation systems, and can be used for equipment rated 2.4 kV, though better value is obtained at voltages levels higher than 4.0 kV. A partial discharge is an electrical discharge that partially bridges the insulation between conductors. The apparent charge q of a partial discharge is described as the charge which, if injected between the terminals of a test element, will instantly change the voltage between its terminals by the same amount as the partial discharge. The partial discharge inception voltage is the lowest voltage at which partial discharge levels are observed under defined conditions, when the voltage applied to the test object is gradually increased. The partial discharge extinction voltage is defined as the voltage at which the partial discharge surpassing defined level cease under qualified conditions when the voltage is decreased. It is known that partial discharge is unstable. Some factors affecting partial discharge are:

- Variation in the machines of the same rating of a certain manufacturer over the course of years. When cross comparing PD test results on different machines, it is mandatory that test instrument bandwidth and noise separation methods are identical, that the type of sensors are same, and also that the operating voltages of the machines are same.

- Changes of the PD activity in healthy insulations in machines of the same electrical specifications produced by different producers
- PD measurements cannot be expected to discover all the problems in electrical insulation.
- Voltage, load, temperature, humidity, vibration, pressure
- Background noise
- Different test techniques can give different results, and precise limits are difficult to establish.

Hence, it becomes challenging to establish norms of PD activity, though many attempts and statistical information is available. A manufacturer’s test lab has its own regulations and acceptance levels. These differ from manufacturer to manufacturer. The standards discussing online PD measurements avoid stating the specific levels or quantities to determine acceptable limits. Table 3 presents statistical data for air-cooled generator stators. Therefore, the focus is on trending. PD measurement completed over a long period will give tangible results provided it is ensured that all dynamics and test conditions stay exactly the same for each test interval. This may be the challenging task.

Table 3. Distribution of Qm for air cooled generator stators

Operating volts	2-4 kV	6-8 kV	10-12 kV	13-15 kV	>16 kV
25%	7 mV	17 mV	35 mV	44 mV	37 mV
50%	27	42	88	123	69
75%	100	116	214	246	195
90%	242	247	454	508	615

ONLINE VERSUS OFFLINE ANALYSIS

Typically, offline measurements are more global in their coverage however they do not represent the real operating conditions. The offline measurements are used at longer intervals, typically, 6 – 12 months. Many problems can show in shorter time span and avoid detection. If a bigger discharge activity is discovered, then the questions arise: when the problem started, how fast it is degrading and will continue to degrade, and if prompt action is needed? On the other hand, permanent monitoring does give a better trending and eliminates some of the variables discussed above, yet it may not be proper. For instance, partial discharge measurements on motors and generators may cover small portion of the windings near the sensors. Some benefits are that no outage is needed to complete the tests, which are completed under real operating conditions. Temperature dynamics, humidity, and load current can be correlated to partial discharge activity. Also, a chance for remote diagnostic is given. PD measurements are applicable to cables, switchgear, rotating machines, transformers, bus bars, etc.

TEST TECHNIQUES

The following test techniques could be used:

- offline PD test to measure the PD activity
- online PD measurement or EMI (electromagnetic interference) for PD during normal operation
- ultrasonic probe test
- transient voltage or corona probe or EMI test to find PD
- blackout or ultraviolet imaging

Sophisticated electrical interference technology is needed to suppress electrical noise to prevent false indications. Partial discharge happens in an air-filled void, and the flow of electrons through the void multiplies. This ends in a current pulse of short duration, normally a few nanoseconds. A Fourier transform of the created pulses shows frequencies up to several hundred MHz. The test instruments are coupled to equipment through a high voltage capacitor (also Stator Slot Couplers SRC), which transfers high frequency PD currents, giving high impedance to power frequency. In metal-clad switchgear, PD sensors can be used. They use the natural capacitance between the CT and main bus, and couples the high frequency signal to the secondary of the CT windings. The PD current that goes through the capacitor induces a voltage that can be shown on a CRT or spectrum analyzer. Modern detectors are sensitive to many MHz. Every PD will make its own pulse, and the key measurement is the peak magnitude of the pulse Q_m. Also, pulse count is crucial and may be sometimes more important than Q_m.

The major quantities that have to be recorded are Q_m, partial discharge current, PD power loss, pulse discharge repetition rate, etc. The PD intensity considers both the amplitude and the pulse count. Partial discharge on rotating machines suggests one extra parameter, that is, normalized quantity number (NQN). It is expressed as:

$$NQN = \frac{FS}{G \times N} \times \left[\frac{\log_{10} P_1}{2} + \sum_{i=2}^{N-1} \log_{10} P_i + \frac{\log_{10} P_N}{2} \right]$$

Where:

Pi - number of pulses per second in magnitude window i

N - number of magnitude windows

G - Gain of partial discharge detector

FS - maximum magnitude window in millivolts

Pulses with high repetition rate have lower contribution to NQN, than the pulses with low repetition rate. Even though normalized, the NQN changes with the PD detector sensitivity. Figure 29 presents a PD measurement, and shows that PDI is not dependent much upon number of magnitude windows. The complete PD is the sum of positive and negative quantities. This is not true for NQN, which changes up to three times within the selected range of magnitude windows (Figure 29). PD in different phases can be measured and cross compared. This may show a defect, when cross compared with similar results over a period of time.

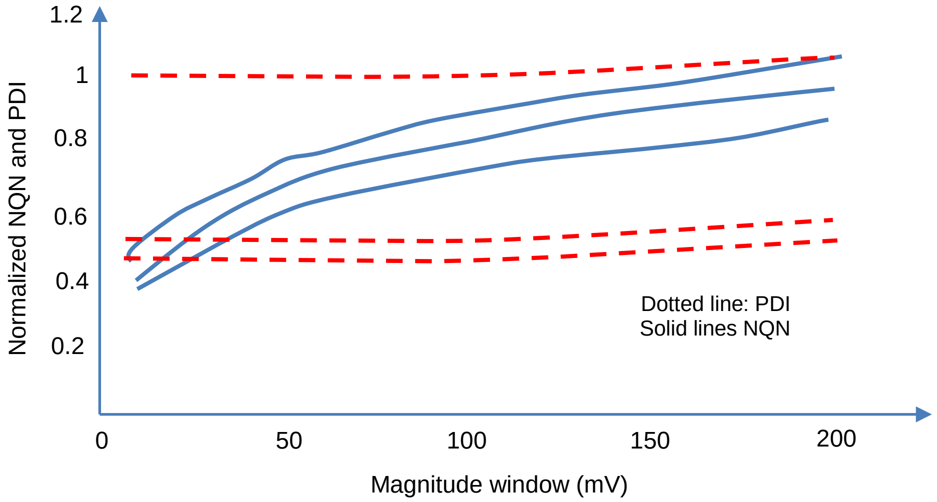


Figure 29. Normalized NQN and PDI

In a rotating machine, if there is one dominant deterioration mechanism, the PD assessment can sometimes give the approximate position. The same applies to PD measurements in underground cables. The faults have been localized in cable installations with PD measurements to a close resolution, particularly with offline testing. Figure 30 presents the PD measurements in a generator over a long period.

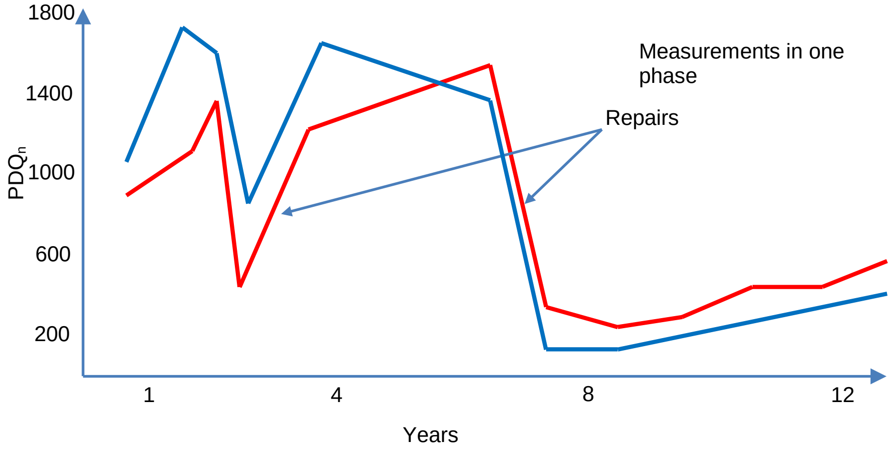


Figure 30. Generator PD measurement data over the course of years

CURRENT SIGNATURE ASSESSMENT: ROTATING MACHINES

Current signature analysis (CSA) can discover breaks or cracks in the bars and rotor short-circuit rings of squirrel-cage induction motors. It is completed online and close to full load operation. Due to magnetic coupling between the rotor and stator windings, the current transferred into an induction motor is not strictly dependent upon the power supply voltage and is affected by the rotor condition. The stator current is assessed through a current transformer and evaluated with spectrum analyzer. Particular dynamic range and frequency resolution are required in the measurements, and current magnitudes are measured in dB. If there are no breaks, there will be no sidebands. A current signature as presented in Figure 31 does show breaks. At the moment, there are no IEEE or IEC regulations on performing and interpreting CSA results.

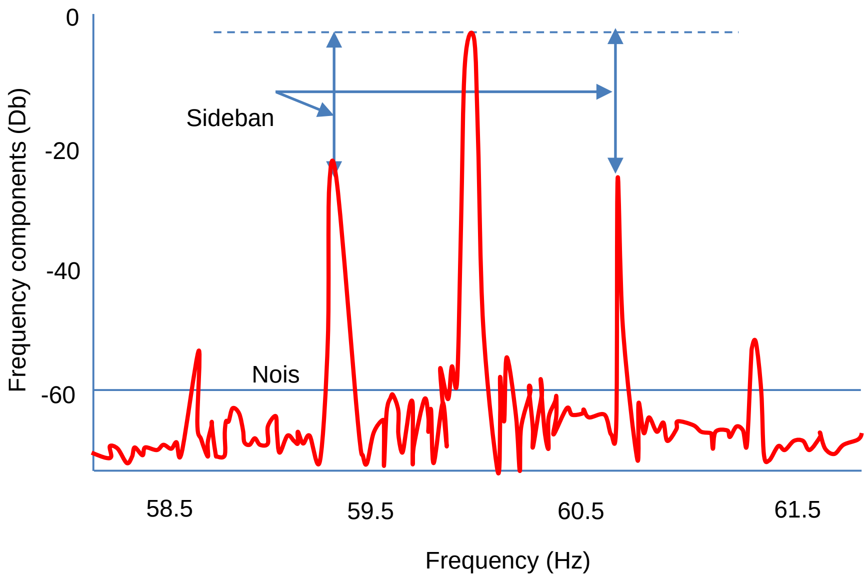


Figure 31. CSA of a rotating machine showing breaks in rotor bars

DISSIPATION FACTOR TIP-UP

The term dielectric is synonymous with insulation. A dielectric or electrical insulation, when put between two electrodes at different potentials, allows only a small negligible current to flow. Ideally, no current should flow through a perfect dielectric. An equivalent circuit and accompanying phasor diagram can be drawn as presented in Figure 32. For a perfect dielectric, the phase angle δ, called the loss angle *or* dissipation factor, needs to be zero. As the insulation deteriorates, this angle increases, and measurements of the loss angle have been used to cross compare the deterioration over a period of time. It can be written:

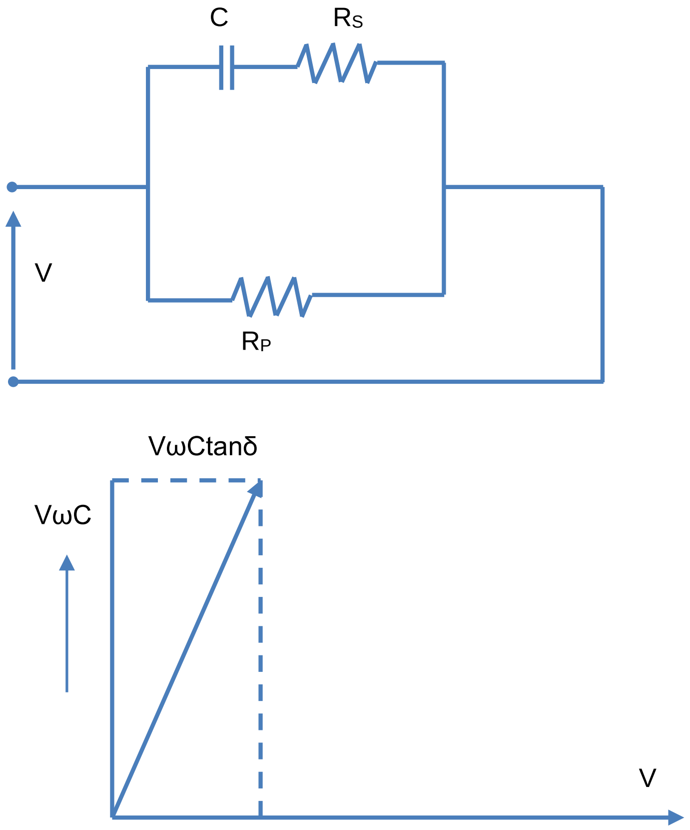


Figure 32. Model of a leaky dielectric and loss angle

$$\begin{aligned} \delta &= \tan^{-1} 2\pi f C_s R_s \qquad R_P = 0 \\ &= \tan^{-1}\left(\frac{1}{2\pi f C_P R_P}\right) \qquad R_S = 0 \end{aligned}$$

For insulation materials that have a low dissipation factor, the power factor is same with it. When the tests are completed at both low and high voltage and increase in value over-voltage (tip-up) is evaluated, it depends on the amount of partial discharge activity in the insulation system.

For arc flash hazard reduction, a prior understanding of the imminent failure is valuable information. A timely intervention and maintenance can prevent a failure, equipment defects, and unnecessary fault and shutdowns. Considering two electrical systems, one not so well designed but better maintained and the other much better designed, but without essential maintenance and diagnostics. The system that is not so well designed but better maintained and operated introduces lower arc flash risks.