Mitigation of Arc-Flash Hazards and Reduction of Costs by Selective Arc-Flash Protection

L. Kumpulainen, S. Dahl

Vamp Ltd, Finland

J. Ma

Vamp Ltd, China

1 ABSTRACT

This paper describes causes and characteristics of arc-flash faults, and gives an overview of existing arc-flash protection methods. The methods include e.g. arc-resistant switchgear, bus differential protection, zone selective interlocking, current limiting devices, and optical sensing based protection. Criteria of evaluation of the methods are proposed. The preferred dual-sensing methodology is explained more in detail. Current approaches to prevent arc-flash incidents and existing ultra-fast arc eliminators are introduced.

2 INTRODUCTION

Arcing faults cause both personnel hazard and significant economical losses due to damage to equipment and interruption of processes. The awareness of these risks has recently significantly risen, and methods to mitigate the consequences of arc-flash incidents have been introduced. This paper summarizes the features and consequences of electric arcing faults, compares different protection methods and introduces a fast, selective arc-flash mitigation technology.

3 ARCING FAULTS

3.1 Causes of arcing faults

Majority of arc-flash faults in switchgear is caused by human errors. Entering into a live panel or field, careless use of tools or leaving temporary earth connected are common operating errors. Other typical causes of arcing faults are loose connections, insufficient mechanical dimensioning, equipment malfunction, contamination or degradation of insulation, and animals.

3.2 Characteristics of electric arc flashes

Arcing fault is short circuit via ionized gas (air) between one live part and ground or between live parts. High power arc-flash faults can be characterized as electrical explosions. They release large amounts of energy in the form of radiant heat, intense light, and high pressure waves. The temperature of the plasma can reach 20.000 K. The increase of the temperature expands the volume of the air causing a pressure wave. Because of the high temperature, circuit components can change physical state from solid to vapor. E.g. copper expands by a factor of 67.000 in vaporizing, which significantly increases the pressure. In addition to danger caused by radiation, heat and pressure wave, there may be shrapnel and toxic gases, causing additional personnel hazard. [1], [2]

Most arc-flash faults start as single-phase to ground faults and develop into three-phase faults. This emphasizes the importance of early detection of the arc in order to rapidly clear the fault.

Arc current is not the same as the bolted fault current, because of the arc resistance. Because electric arc is more or less unpredictable, exact values for arc resistance or current cannot be given. Calculation formulas in standards are based on extensive experimental data. Arcing current is always lower that the bolted fault current [3], [4]. Especially in low voltage, the arcing current can be less than half the value of the bolted fault current. It is important to note that low fault current may lead to longer fault clearing time and thus higher risk and damage. Both high and low arcing currents can be hazardous.

3.3 Hazard and damage caused by arcing faults

From the arc characteristics described above it is clear that the risk of personnel hazard is very high. It has been estimated that e.g. in the U.S.A. every day 1-2 people die in arc-flash accidents [5].

Significant damage to the equipment, up to total destruction of the switchgear, is possible. It should also be noticed that in addition to direct repair cost the indirect costs of arc-flash fault, lost production, compensation to customers etc, can be high.

The consequences of an arcing fault depend on the incident energy. The incident energy is defined as the amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event. Thus there are four factors that determine the energy: distance, voltage, current and time [1].

4 ARC FLASH PROTECTION METHODS

4.1 Arc flash prevention

Because human error is one of the most typical causes of arc-flash faults, education, instructions and careful working procedures are an important and cost-efficient way to prevent faults. A more technical approach aiming at arc-flash prevention is preventive maintenance of the equipment. The most developed methods are on-line monitoring systems. On-line monitoring of partial discharges, especially in cable compartments, has not yet been widely implemented, but it is a potential method. Infra-red and ultra-violet detection systems have also been suggested for on-line monitoring of switchgear. On-line monitoring of equipment possibly reduces the number of faults caused by failure of equipment, but they can not prevent arc-flash incidents caused by human errors.

On-line analyzing of currents has been proposed for preventive arc fault detection in a few scientific papers [6], [7]. The focus in these investigations has been the question, whether the changes in harmonic spectrum could be the basis for preventive arc detection.

Developing faults can be detected in their early stages by smoke detectors. When detectors are connected to protection relays, in some cases it is possible to totally prevent arcing and avoid major damage.

System earthing has influence on the magnitude of earth-fault current. Because many arc-flash faults initiate as single-phase-to-earth faults, systems with low earth-fault current reduce the probability of serious arc-flash incidents. Some researchers recommend high resistance grounding for low voltage systems for safety reasons [8]. High resistance grounded systems, having a resistance between the neutral point and the earth, have been applied mainly in low voltage systems. In phase-to-phase faults there is no difference between solidly grounded and high resistance grounded systems.

4.2 Mechanical protection methods

4.2.1 Arc-resistant switchgear. Arc-resistant switchgear provides a mechanical barrier between the operator and fault and re-directs the energy of the arc blast away from the operator [9]. The gear may or may not survive the internal fault [10]. This means that the outage can be long. From safety point of view, arc-resistant switchgear provides protection to personnel as long as the doors are closed. However, open doors are very common in practice, and in injury scenarios [11].

4.2.2. Remote racking and operation. Increasing operation and monitoring distance to dangerous equipment is one option to improve safety. This can carried out by remote control technology, so that the switching can be done outside the dangerous area.

4.3 Reduction of incident energy by limiting fault current

The incident energy of an arc-flash depends on voltage, current, and time. System voltage is normally not one of the issues one can change, when thinking about eliminating arc-flash. On the other hand, fault current can be limited.

4.3.1 Transformer sizing and current limiting reactors. System impedance can be increased by selection of transformers, and current limiting reactors. The drawback of increasing of system impedance is the increase of losses and increase in costs.

4.3.2 Fault current limiters. In some cases pyrotechnic-based fault current limiters could be used in order to limit arcing current.

4.3.3 Current limiting fuses. One of the best known technologies used in arc current limiting is current-limiting fuses. When the current is high enough, current limiting fuses extinguish their internal arc before the zero of the current is reached. This shortens the duration of the arc, and reduces the energy. Current limiting fuses provide current limiting action only in cases of very high fault current [10]. When current-limiting fuses do not operate in their current limiting range, clearing times can be significantly longer [1], [12]. In fact, lower current can lead to higher incident energy level.

When carrying out arc-flash fault risk analysis both the highest possible and the lowest possible fault current should be analyzed. The risk caused by high fault current is obvious, but also low fault current can be problematic, because low current can lead to longer operation time of relays or fuses, leading to longer arcing time. The fact that in low voltage the arcing current is often less than half of bolted fault current should also be taken into account.

4.4 Reduction of incident energy by reducing arcing time

High-speed relaying is often the easiest way to reduce incident energy. Because speeding up of normal protection by reducing operation times is normally not enough, dedicated protection is needed. There are several methods for decreasing the arcing time. In the following, the main features of the most common methods are shortly described.

4.4.1 Bus differential protection. Bus differential protection is a relatively fast method (typical tripping time 1-2 cycles, 15-40ms) for bus protection. High-impedance bus differential protection is very costly, because it requires dedicated current transformers and extra wiring. The relay measures the voltage across its internal impedance, and if the voltage is above the pickup value, the relay trips.

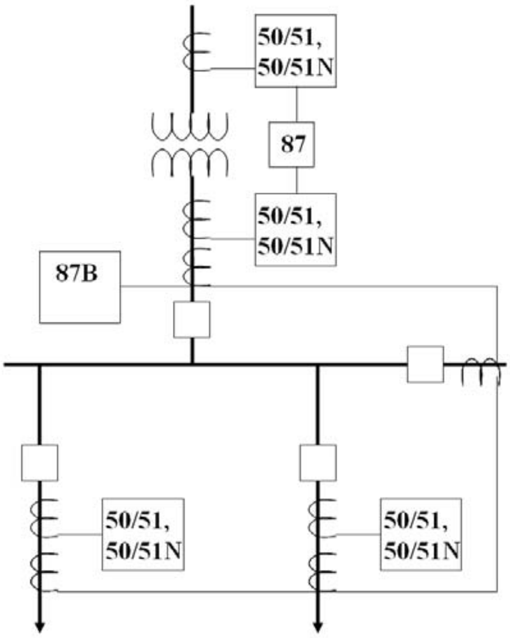

Figure 1. The principle of bus differential protection.

Low-impedance bus differential scheme does not require dedicated current transformers, but the relay settings are more complex than in high-impedance bus differential scheme. Neither of the schemes provides protection against faults in the feeder cable compartment. There is also concern regarding the possibility of the saturation of the current transformers in close-in external feeder faults, leading to false operation [13].

4.4.2 Zone selective interlocking. Fault clearing times of 3-10 cycles can be reached by zone selective interlocking. The method requires communication between the relay of the main circuit breaker and the relays of feeders. If the downstream relay picks up, it sends a blocking signal to the relay of the upstream breaker. If the downstream relay does not see the fault, the relay of the main circuit breaker does not receive a blocking signal, and the main breaker can be opened almost instantaneously.

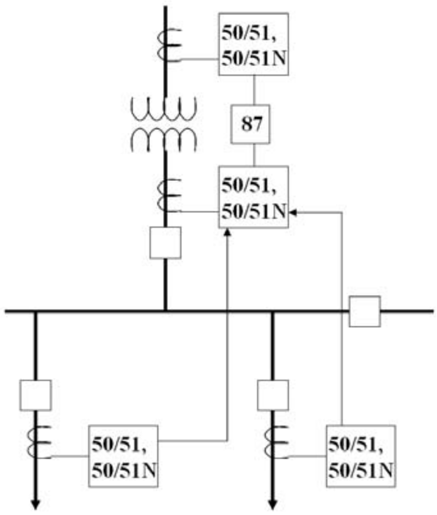

Figure 2. The principle of zone selective interlocking.

4.4.3 Instantaneous tripping during maintenance. Safety of the personnel can be increased by maintenance switch that enables instantaneous tripping during maintenance work. There are products available for both MV and LV systems, and this scheme can be performed by existing numerical relays provided that the relays contain multiple setting groups or multiple instantaneous overcurrent stages. From asset protection point of view this method is effective only during maintenance work.

4.4.4 Optical sensor based arc flash protection. An arcing fault produces instantaneously radiation that can be detected by analyzing visible light. Optical sensor based arc flash protection enables very short fault clearing time. In order to avoid false tripping, overcurrent condition is normally combined with light detection (dual sensing). Because majority of arc flash faults start as single phase faults, it is essential to measure the neutral current as well, because this way it is possible to clear the fault in its early stages.

The operation of the arc flash protection is based on simultaneous light and phase overcurrent or ground overcurrent conditions. For special purposes, “light only” condition can also be used. [14]

The tripping of the circuit breaker is initiated by a dedicated arc flash protection relay or by a common numerical protection relay equipped with arc flash protection option. The trip is initiated within 7ms (dedicated arc flash relay) or within 15ms (numerical protection relay with arc flash option). If semiconductor output instead of conventional trip relay is used, even shorter trip initiation time can be achieved.

Figure 3 below shows the test result of switchgear exposed to 50kA fault for 500ms burning time. Figure 4 shows the result of same 50kA fault condition with light and current based arc flash protection system resulting in total fault burning time of less than four cycles. The photographs dramatically illustrate the importance of the reduction of the arcing time to mitigate damage to the equipment.

Figure 3. Test result with 500ms arcing time.

Figure 4. Test result with light and current based protection.

Incident energy comparison verify the importance of the speed of the protection. Figure 5 illustrates the impact of arcing time on incident energy by comparing different protection methods. The incident energy levels have been calculated according to standard IEEE Std 1584™-2002 [15].

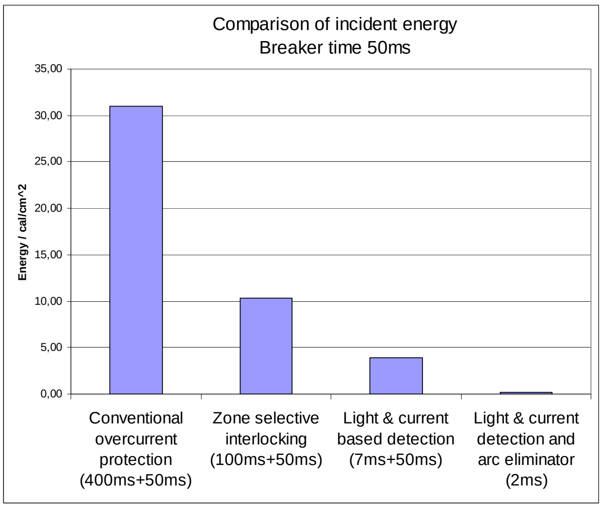

Figure 5. Comparison of incident energy of different protection methods.

5 IMPLEMENTATION OF OPTICAL SENSOR BASED ARC FLASH PROTECTION

5.1 Dedicated arc flash protection relays

Arc flash protection is usually implemented by separate system using arc flash detectors connected to dedicated arc protection relays. Overcurrent, earth fault etc. protection is carried out by other relays. A comprehensive, selective arc flash protection system comprises of arc flash sensors, slave units collecting data from the sensors, and a master unit or several units for final collection of all the sensor data, measuring the current and tripping the breaker, if both light and overcurrent are detected.

Arc flash sensors (Figure 6) can be point sensors or fiber optic sensors. Selection of sensor type depends on the application. According to practical experience, fiber optic loops are cost effective to apply for low voltage switchgear or motor control centre with multiple compartments. Advantages of point sensors are easy new and retrofit installation and provision of exact fault location indication as sensors are installed in each protected compartment. The safety of the maintenance personnel can be enhanced even further by personal point sensor, connected to clothes. Regardless of the sensor type, it is essential that the arc flash protection system has self-supervision including the sensors and cables.

Figure 6. Point sensor and fiber optic sensor.

In multi-zone arrangements, master units must be able to interchange data. Information on activated sensor can be distributed to all master units, so that all master units which detect overcurrent can open the circuit breakers in their zones. Similarly, information on locally detected overcurrent can be passed to other units as a trip condition, if one unit detects light but no overcurrent. Figure 7 presents an example of selective multiple zone protection.

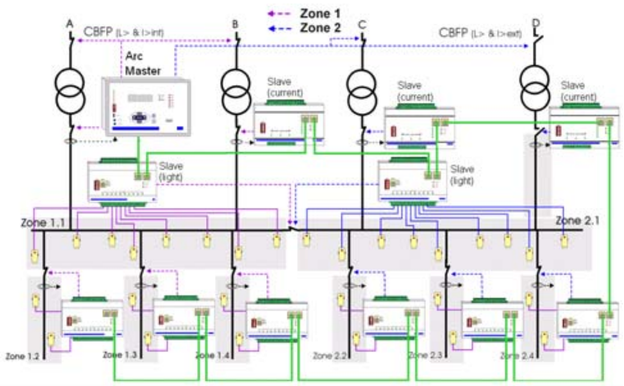

Figure 7. An example of selective arc flash protection with dedicated arc flash protection system.

Cost effective arc flash protection is needed e.g. in wind power plants and in secondary substations. In this kind of environments, stand-alone units without master units can be applied. Figures 8 and 9 present examples of point sensor based arc flash protection in a wind power plant. In Figure 10, an example how fiber optic loop sensors can be installed to provide comprehensive protection.

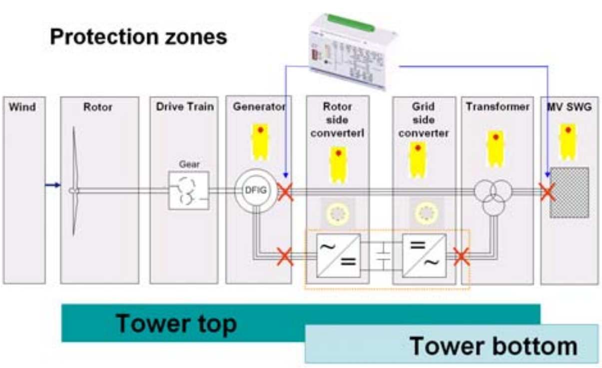

Figure 8. Protection zones of a wind power plant equipped with point sensors.

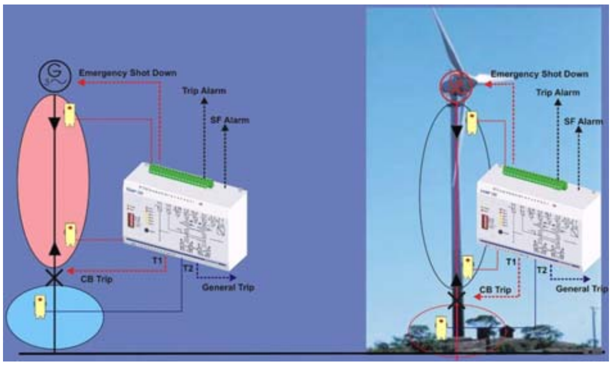

Figure 9. Arc flash protection of the tower cable and the MV switchgear in wind power plant, point sensors.

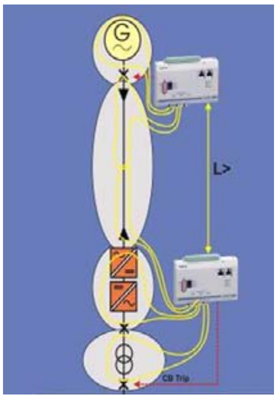

Figure 10. Fiber optic loop sensor based arc flash protection of a wind power plant

5.2 Numerical relays equipped with arc flash protection option

Numerical protection relays can be equipped with arc flash protection option, which is a very cost effective way to implement arc-flash protection. In practice this means sensor inputs to which the arc flash sensors can directly be connected. This way the total cost of the protection concept is minimal. The arc sensor input may include e.g. two inputs for arc sensors, one binary input and one output for receiving/sending arc sensor data to other relays. The relays include high-speed overcurrent and earth fault stages dedicated to operation with the arc flash sensors.

The selectivity of arc flash protection can be increased by connecting arc flash sensors of the outgoing feeder to the overcurrent relay of the feeder. If an arc fault occurs in the feeder area, only the feeder breaker will open, leaving the rest of the substation operational. This is very beneficial, because many arc faults occur in cable compartments. Figure 11 presents an example of arc flash protection carried out by common numerical relays with arc flash protection option.

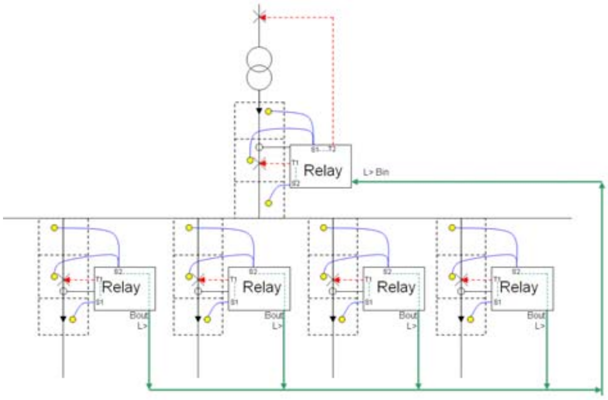

Figure 11. An example of selective protection using common numerical relays equipped with arc flash protection option.

5.3 Ultra-fast arc flash protection

With light and current based arc flash protection the arcing time consists of the operation time of the protection relay (7-15ms) and the operation time of the circuit breaker (typically 50-80ms). In some cases even shorter arcing time is needed, often in order to limit the rise of the pressure. For these purposes, arc quenching devices can be applied. When the arc is detected by the arc protection relay, the relay trips the quenching device within 2-5ms and sends the tripping signal to the circuit breaker within 7ms. The quenching device makes the short circuit at ultra high speed, and the arc is quenched. The bolted short circuit current flows through the quenching device until the circuit breaker opens.

Combination of arc quenching device with current limiting fuses is a potential solution to overcome the limitations of current limiting fuses, and this combination also mitigates the stress to the equipment by reducing the fault clearing time.

For low voltage systems the quenching device makes the busbar potential free within 2ms. Arc eliminator for medium voltage system is able to extinguish the arc within 5ms.

6 CRITERIA FOR THE COMPARISON OF THE METHODS

When selecting arc flash protection method, speed and the reduction of incident energy are the most important but not the only criteria. Because of the severe consequences of the possible failure of the protection, the reliability of the protection method should be emphasized. This favors the requirement of system self-supervision and ability to operate also with low fault current. Especially in process industry with high outage costs, selectivity is a one of the key issue. In many cases arc flash protection is installed in existing switchgear, which requires retrofit option. Economical justification should include at least a rough evaluation of worst case fault scenario.

7 CONCLUSION

This paper has described methods to mitigate arc flash hazard. Because arcing time is the most critical factor, fast, optical sensor based protection methods are preferred. Other important issues are the selectivity and self-supervision of the protection system. Asset protection along with safety aspects should be taken into account as in any system design. Combination of sensing of light and overcurrent has proved to be a very efficient method. This method can be applied by dedicated arc flash protection system or by using common numerical protection relays equipped with arc protection option. For the most demanding cases, ultra fast arc eliminating technology is available.

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