ARC PROTECTION AS INTEGRATED PART OF LINE PROTECTION RELAYS

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ABSTRACT

This paper first presents general characteristics of an electric arc. Possible damages and reasons which may cause arcs in a switchgear are discussed. Ways to limit the damages caused by the arc short-circuit are presented. Different ways to implement arc protection is discussed. New type of relays with integrated arc protection function are finally introduced.

INTRODUCTION

An electric arc short-circuit is an infrequent switchgear fault where an explosion-like heat and pressure-effect may cause large material damage and jeopardize the job safety of the opeation staff. The goal of the arc protection is to detect the arc and minimize its burning time thus protecting people and property. The burning time is usually minimized by cutting off the current path feeding the arc.

Generally arc protection is implemented using a separate arc protection system. In this system arc detectors are connected to specialized arc protection units.

New type of line protection relays include sensor inputs and the arc sensors can be directly connected to them. In this way arc protection can easily be integrated as part of the total protection concept with minimal additional cost.

An overcurrent relay with integrated arc sensor inputs can be used to build short-circuit and arc protection of one feeder in a switchgear. The relay will selectively trip the breaker of the feeder in case of arc fault is detected in the feeder cubicle. The information about the activation of the sensor can additionally be wired to the incoming feeder's overcurrent relay or arc protection unit. The incoming feeder can thus be tripped if there is an arc detected anywhere inside the switchgear.

The following general information about the arc short-circuit's features, damages, reasons and ways to limit its damages is mainly based on references [1] and [2].

FEATURES OF AN ELECTRIC ARC

An electric arc is formed if current flows from one electrode to another via a channel of ionized gas. The arc phenomena can be intentionally caused like in an arc furnace or in arc welding. Arcing also regularly happens in normal switching operations. Electric arcing is especially harmful and dangerous, when it happens unintentionally and irregularly. Lightning and corona effects are examples of this kind of harmful electrical arcs. An electrical arc which causes a short-circuit is the worst possible fault that can happen in a power distribution system.

High temperature

The electric arc is formed when current flows through isolation material - like air or gas - with no galvanic contact. The air becomes conductive when its temperature rises to about 3000°C. To make the air this hot and to start an arc some kind of ignition is required. This may be e.g. a thin wire which burns away when current flows through it.

The temperature of a burning arc is depending on the fault current, arc voltage and cooling conditions. In short-circuit situations the temperature in the centre of the arc may be up to 10.000 …20.000 K. In the contact points the temperature is smaller, about 3000...4500 K.

Ionisation

In high temperature air and other gas molecules are broken to atoms and further to ions and electrons. This causes the gas to conduct electricity.

Light and other radiation

Part of the arc energy flows to the environment as infrared, ultraviolet and visible light radiation. Also radiation in the radio frequencies is generated. The radiation is transmitted by the arc itself and the materials heated up by the arc.

At the brightest the light will be between 100..200 ms after the ignition of the arc until smoke and metal steam will reduce the sight. Some measurements have indicated 9000 lux brightness from 6..7 meters.

The total radiation may be 1....10 W/cm^2 at a distance of 1,5 meters. This is rather high value compared e.g. to the radiation from the sun on the surface of the earth, which is about 0,1 W/ cm^2.

Movement of the arc

The thermal force tries to lift the centre of the arc upwards, because the air in the centre is warmer. The lifting of the hot air upwards causes air to move, this convection force further pushes the centre of the arc upwards. These forces make the electric arc to bend to its characteristic arc form. The current flowing due to the shortcircuit creates elctrodynamic force which makes the arc to move to the direction of the energy flow in the circuit. In swichgears the arc moves to the end of the conducting bars or close to through-holes.

Voltage and resistance

In medium voltage switchgear the arc voltage is about 500...1000 V. In low voltage circuits the arc voltage is about 300 V. The resistance of the arc is usually less than 0,1 Ω. In short-circuit calculations this resistance can often be neglected.

Power and energy

The total power and energy of an arc short-circuit depends on the number of separate electric arcs burning in the system. There may be one arc burning between two phases or there may be three or more arcs burning between all the phases, this depends on the mechanical construction of the switchgear. The power of the arc may be somewhere between 8...60 MW depending on the short-circuit power of the switchgear.

The energy of the arc is consumed to (the percentage figures are only approximate values):
- heating of the air (40...65%)
- heating of the materials (~10%)
- forming of the pressure (~3%)
- melting and evaporation of electrode materials (~7%)
- melting and evaporation of other materials (~5%)
- electrode thermal losses and radiation (~8%)
- radiation from the arc itself (~7%).

DAMAGES CAUSED BY ARC SHORT-CIRCUIT

The energy released from the electric arc can cause both material and personal damages. In most cases the arc fault causes also economical losses due to interruption of energy distribution.

FIGURE 1: A cubicle damaged by arc short-circuit.

The series of events related to an electrical arc can be divided into 4 steps, compression, expansion, emission and thermal phase. First the gas will be compressed as the pressure rises in closed space. When the pressure relief valves opens the gas expand and it will flow to the ambient room or outside. In case this works properly the pressure will decrease inside the cubicle and in the switchgear room.

The compression and expansion time totally is approx. 5...15ms. After this the radiation and thermal phase will follow. The radiation phase lasts for some hundreds of milliseconds and the thermal phase will continue until the arc is extinguished

Pressure effect

The burning arc will heat up the ambient air, causing expansion of the air and create a huge pressure inside the cubicle of a switchgear.

In the worst case the doors of the switchgear may open and weak walls or ceilings of the switchgear or the building may be broken due to the pressure. Additionally the pressure may throw out loose or detached parts from the cubicle.

New switchgear is planned to withstand high pressure. In tests, over 120 kPa (1200kg/m2) pressure has been measured. This can be achieved by pressure relief valves or openings.

Burning effect

The burning effect of arc will be on the electrodes, cubicle doors, walls and on the busbar. There will be burning gases and hot particles exploding out to the environment.

The arc will melt and evaporate electrode material. Part of melting material is splashed around and part of it will be mixed with the air. The electrodes will suffer most in those spots where the arc will stay for a longer time. The burning effect may cut busbars and wires, holes may be burned to doors, walls or ceilings and equipment may be destroyed. In addition to the burning effect of the arc itself the arc may set up fires in the materials of the building or in the cables.

Hot or even burning gases may explode out from the cubicles causing damages to the property or humans. The clothes of a person standing by may catch fire due to the hot gases. The gases may also be toxic because they may contain e.g. carbon monoxide and copper or aluminium steam.

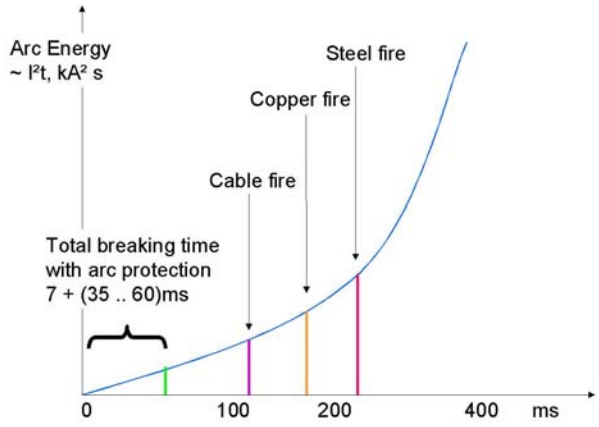

FIGURE 2: Arc energy as function of burning time. Points where metal parts start to burn are indicated. Arc protection will function before cable fire starts.

Effects of radiation and sound

Direct radiation from the arc usually does not cause direct danger to persons. This is because the radiation level is below the dangerous level (25 W/cm^2). The bright light can anyhow cause temporary blindness which combined with loud sound effect might cause the worker to go into shock and this will increase the risk of injury.

REASONS TO ARC SHORT-CIRCUITS

The most common reasons to arc short-circuits can be classified into two main groups 1) human and operational errors and 2) technical reasons.

Typical human and operational errors are
- work in a wrong cubicle
- operation of a wrong isolator
- forgetting to ground the working area
- forgetting to test the presense of voltage in the working area

Technical reasons to arc short-circuits:
- faults in equipment and false operation of equipment
- ageing of insulation and mechanical wear
- overvoltage
- overheating
- moisture, dirt
- equipment wear

- corrosion
- foreign objects (e.g. tools) in the switchgear
- small animals
- installation errors
- bad wire and busbar connections

WAYS TO LIMIT THE DAMAGES CAUSED BY ARC SHORT-CIRCUITS

The damages caused by arc short-circuits can be limited in principle in three ways:
- improving the construction of the equipment
- limiting the arc short-circuit power
- limiting the arc burning time

Improvements to the construction

The construction of the switchgear can be improved so that they are able to withstand the pressure and burning effects of the arc. The pressure withstand can be improved with proper desing of the pressure vents and channels. The damaged area can be limited by dividing the swithgear to smaller cells. The arc withstanding of a certain switchgear type must be checked by testing.

The costruction must be such that it limits the possible injuries to working personel. Poisonous gases must be conducted to a safe direction and it should be easy to escape from the vicinity of the switchgear.

Limiting the short-circuit power

This is usually not possible because the use of electricity is increasing all the time and the switchgears must handle larger currents.

Limiting the arc burning time

The best way to limit damages of an arc short-circuit is to limit the arc burning time. The burning time can be limited by tripping off the breaker, which is feeding the arc current. This will effectively limit both direct and indirect damages. Especially when arc is developed during work in the switchgear the short arc burning time has a great value.

Rules of tumb for different arc burning times:

- 35 ms: no significant damage to persons or switchgear, which can often be taken in use after checking the insulation resistances
- 100ms: small damage, requires cleaning and possibly some minor repair before swithchgear is taken in use again
- 500ms: large damage both for persons and the switchgear, which must be partly replaced.

The arc burning time is the sum of the time to detect the arc and the time to open the correct breaker.

ARC DETECTION

The goal of arc protection

The goal of the arc protection is to protect property and people in case of an electric arc fault by limiting the arc burning time. To do this **the arc protection must first detect an arc and then cut the flow of current**. The flow of arc current is usually cut by opening a cicuit breaker. The other possibility - especially in low voltage systems - is to cause an intentional galvanic short-circuit, which will drain off the current flow from the arc thus extinguishing it.

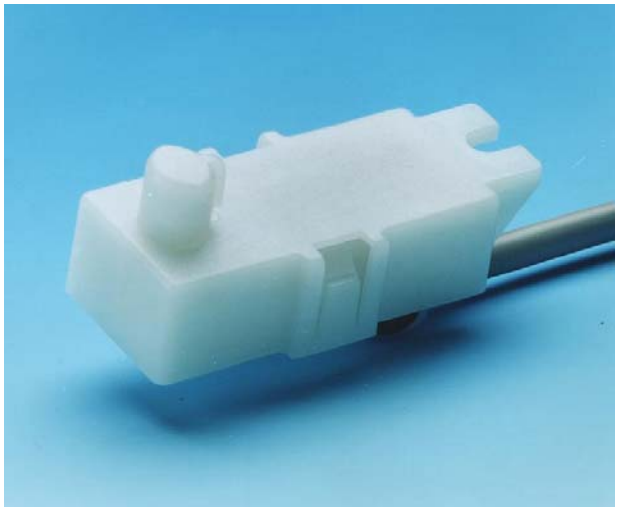

FIGURE 3: Light sensor for detecting electric arc.

Arc detection methods

Arching is accompanied with radiation in the form of ligth, sound, heat and electromagnetic waves. The

presence of of the arc can be detected by analysing visible light, acoustic waves, infrared or radio frequency radiation [3]. Even the pressure wave caused by the arc has been used for detecting it. The most commonly used metod is detecting visible light.

To avoid errorneous trips the presence of short-circuit current together with one of the above mentioned arc indications is usually used as condition before making an arc short-circuit trip.

Partial discharge detection

Damaged inslution can lead to partial discharges (PD's) which bridge only part of the insulation clearance. To begin with, these PD's are not dangerous, but over time they cause ever greater damage to the insulation and their intensity and frequency both increase. If these occurences are not detected in good time and the cause eliminated, the progressive PD's will invevitably lead to a disruptive discharge, causing a complete failure of the operating equipment [4].

Partial discharges can in the end damage the isulators so that an arc short-circuit will follow.

Partial discharges may be detected by using search coils for detecting high-frequecy electrical fields produced by partial discharges.

Detection of partial discharge is an early warning of an arc and an alarm from detected partial discharge is usually given.

ARC PROTECTION WITH SPECIALIZED DEVICES

Generally arc protection is implemented using a separate arc protection system. In this system arc detectors are connected to specialized arc protection units, which take care of the arc short-circuit protection. Line protection is implemented with standard protective relaying.

These devices are usually composed of:
- arc sensors for detecting the arc
  (both fibre loop or photo transistor sensors are used)
- slave units collecting data from many arc sensors
- master unit for finally collecting all the arc sensor data, measuring the current and making the final decision about tripping the breaker if both over current and light is detected.

Some manufacturers use electromechanical relays and some semiconductors as tripping contacts. Some manufacturers implement the arc sensors with photo transistors and some support fiber optic loop as light sensor. In addition to light sensors the system may include e.g. termperature sensors.

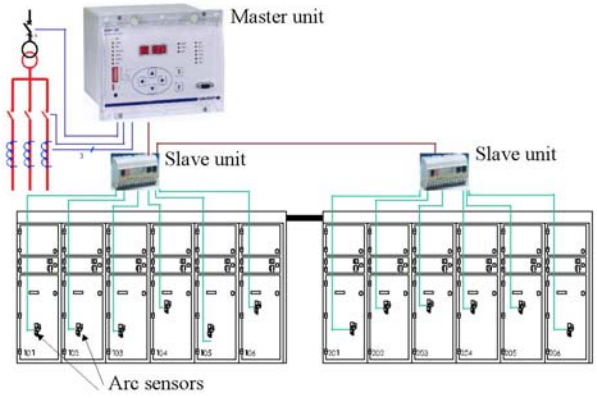

FIGURE 4: Structure of an arc protection system.

The arc protection system opens the main breaker (incoming feeder) of the switchgear when arc short-circuit is detected. If the switchgear contain two or more zones separated by breakers then the system can be built to open only the breaker of the faulty zone and the breaker(s) separating the zones.

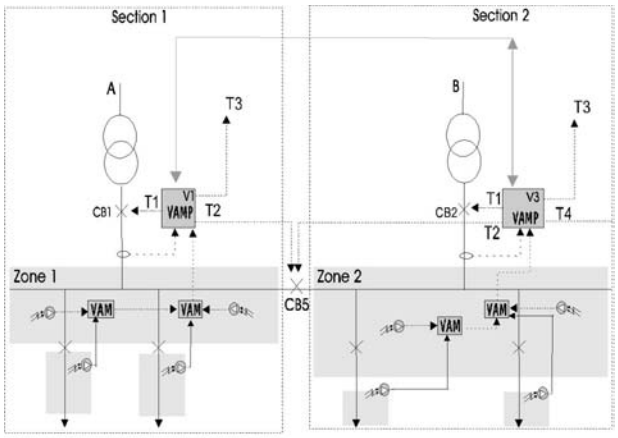

FIGURE 5: Arc protection system with two protection zones implemented with two master units (VAMP) and multiple slave units (VAM). If fault is detected e.g. in zone 1 then breakers CB1 and CB5 will be opened.

In multi-zone arrangements the master units must be able to transfer data to each other. Information about an

activated arc sensor can be distributed to all the master units in the system then all master units which have detected overcurrent can open the circuit breakers in their own zone. In the same way information about the locally detected overcurrent can be passed to the other units to be used as trip condition if the other unit only detects ligth but no overcurrent.

INTEGRATED ARC PROTECTION

New type of protection relays can be equipped with arc sensor inputs and the arc sensors can be directly connected to them. In this way arc protection can easily be integrated as part of the total protection concept with minimal additional cost. The arc sensor input may include e.g. two inputs for arc sensors and one binary input and one output for receiving/sending arc sensor data to other relays. The relays include high-speed overcurrent and earthfault stages dedicated to operate with the arc sensors.

The protection relay with an arc sensor input can be use to
1) increase selectivity of the arc protection
2) make arc protection more adaptive to feeding point changes
3) implement cost effective arc protection
4) increase the coverage of the arc protection

Increasing selectivity of the arc protection system

The selectivity of the arc protection can be increased, if the arc sensors of an outgoing feeder are connected to the overcurrent relay of the feeder (see figure 6.) If arc fault happens in the feeder area then only the breaker of the feeder in question is opened and the rest of the substation remains operational. The main arc protection system opens the incoming breaker only if there is an arc short-circuit in an area where the outgoing feeders can not measure short-circuit current.

Arc sensors Arc1 and Arc2 in figure 6 should in practice be installed to the cable chambers of the outgoing feeder cubicles. Arc sensors connected to the main arc protection system (e.g. Arc3 and Arc4) would be installed to the truck and busbar chambers.

Adaptive arc protection

The example in figure 6 shows a part of a switchgear where power is normally fed through the transformer but in special situation power may also be brought in via one of the outgoing feeders. Normally the the overcurrent relays take care of the arc protection of the feeders and the arc protection relay protects the busbars section. In case power is fed in through one of the normally outgoing feeders the overcurrent relay of the feeder in question is also used to make arc protection of the switchgear part. This is possible because the information about the activation of the arc sensors of the arc protection system can be brought to the overcurrent relay using the binary outputs and inputs. The arc protection function of the overcurrent relay will trip the breaker whenever it measures arc short-circuit current and either its own or one of the sensors of the switchgear part (sensors Arc 3 and Arc4 in figure 6) detects an arc.

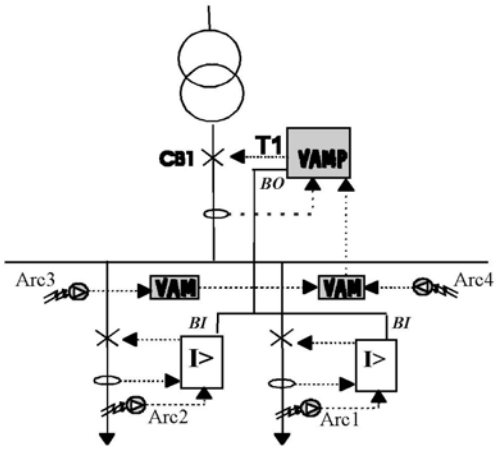

FIGURE 6: Overcurrent relays with arc sensor option and specialised arc protection system (VAMP and VAM). Information about activation of arc sensors Arc3 and Arc4 is also brought to the overcurrent relays via the binary inputs (BI).

Cost effective arc protection system

A low cost arc protection system can be built using protection relays with arc sensors (see figure 7). The information about activated arc sensor can be transferred between the relays using binary inputs and outputs. The relay makes arc short-circuit trip if it detects overcurrent and at the same time its own arc sensor or one of the arc sensors of the other relays is activated. It must anyhow be noticed that the coverage of this kind of system is limited compared to a specialized arc protection system, because the number of arc sensors is limited.

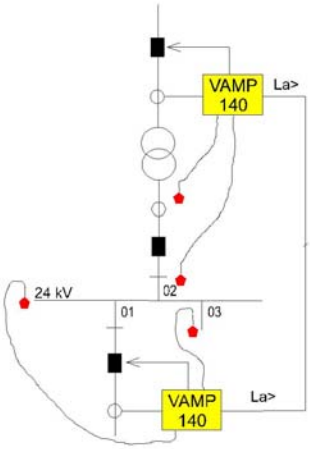

FIGURE 7: Arc protection system using overcurrent relays with arc sensor option. Information about the activation of the arc sensors may be carried between the relays using the binary inputs and outputs (La>).

Increasing the coverage of the arc protection

The protection relays with arc sensor option can be used to measure arc short-circuit in such places where the specialized arc protection system can not measure the arc short-circuit current. An example of this is shown in figure 8.

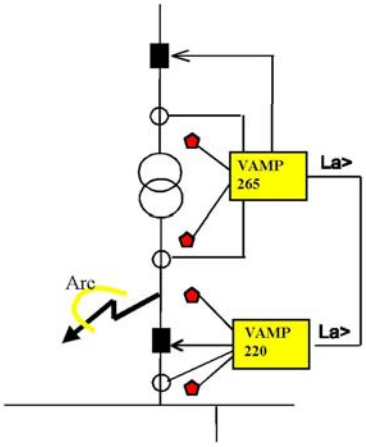

FIGURE 8: Transformer differential relay VAMP 265 with arc option used to extend the coverage of the arc protection system VAMP 220.

If arc short-circuit happens in the indicated place (figure 8) the short-circuit current can not be measured by the VAMP 220 relay. The current can anyhow be measured by the transformer differential relay VAMP 265. The information about the activation of arc sensors is brought from the VAMP 220 relay to VAMP 265 relay using the binary output and input. The VAMP 265 relay opens the breaker when it detects fault current caused by the arc and its own or VAMP 220 relay's arc sensors detects the arc.

CONCLUSIONS

Arc protection is a vital part of switchgear protection due to the possibly drastic damages caused by arc short-circuits. Adding an arc sensor option to standard protection relays provides new possibilities to implement arc protection. The protection can either be implemented with lower than before cost or the selectivity, flexibility and coverage of the arc protection can be increased.

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