CURRENT CHARACTERISTICS OF SERIAL AND PARALLEL LOW CURRENT ARC FAULTS IN DISTRIBUTION NETWORKS

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ABSTRACT

Switchgear protection against over-current and short-circuit usually consists of fuses and circuit breakers. However, these protection devices are not sensitive enough to detect low current arc faults in the range of the rated current of the switchgear. In air insulated low and medium voltage switchgears there are two possible types of low current arc faults, parallel and serial arc faults. Both types of arc faults can cause serious damage on switchgears or even lead to a major arc fault resulting in short circuit.

To be able to develop devices which can detect such low current arc faults, it is necessary to understand the behavior and special characteristics of low current arc faults. Data of field measurements and lab setups were gathered and evaluated to understand the behavior of low current arc faults. Both types of faults, serial and parallel were analyzed. Several characteristics of arc currents could be extracted. Fourier analysis showed that certain frequency ranges of the spectrum can be used as an indication of an arc fault. Due to these analyses it is possible to detect an arc fault by measuring the load currents in the switchgear.

INTRODUCTION

Arc faults are the most dangerous faults in switchgear. Not only can they interrupt the power supply, arc faults may also be dangerous to operating personnel. Previously, it was the role of circuit breakers to detect a high level arc fault and interrupt the power supply as soon as possible to stop the destroying arc. Lately, industry is focusing more and more on the problem of low current arc faults. These kinds of faults cannot be detected by conventional circuit breakers since the current is very often in the range of rated current. Low current arc faults are very difficult to record in the field, so arcs generated by artificial test setups in the lab have to be used instead. To be able to develop reliable arc fault protection devices, it is necessary to understand the characteristics of low current arcs. If unique arc indicators can be found, it will be possible to separate undisturbed operation conditions from arc fault events.

POSSIBLE ARC FAULTS IN SWITCHGEAR AND NETWORKS

Although there has been a lot of progress in the field of safe distribution network operation, arc faults are still present in failure statistics. Most of these failures are short circuits between phases or phase and grounded parts of substations. These kinds of faults are very low resistive and can cause arc currents in the range of many kilo-amperes. Effects on material and staff can be devastating.

The different arc faults described in this paper are considered low current arc faults compared to short circuit arc faults. The arc current is in the range of the rated current of the switchgear. Although low current arc faults can develop into short circuits, they should be detected and taken care of when they are still too small to affect the whole network. Depending on the location of the arc fault they can be divided into two principal categories: parallel faults and series faults [1]. The following section will focus on the special properties of each.

Series arc fault

Although there are no official analyses available, it is widely assumed that series arc faults occur more often than parallel arc faults. They occur if there is a connection failure in series to the connected load as shown in figure 1. Possible reasons are loosening connections of busbars or cable connections with a poor contact. Series arc faults are especially dangerous, because conventional circuit breakers are not able to detect them. The arc current is limited by the connected load ($I_{Load} = I_{Arc}$) and therefore is within the range of rated current of the circuit breaker. The arc will not be detected by the safety device. Even in the range of two to five times the rated current, it may happen that an arc is burning for much too long of a time until the thermal protection of the circuit breaker cuts off the current supply.

Although the gap between the loose busbars is very small at first (< 1mm), it is still possible for an arc to ignite. At first arcing starts at the point of the highest current density. Thermal and electromagnetic forces can cause the arc to move to other locations. The generated heat from the arc melts copper out of the busbars and can also bend them further apart. Since arc ignition and behavior has many influences, it is not possible to describe a standard series arc, although this has been attempted especially in residential wire. The cable jacket plays a big role for arc ignition and duration [2]. In switchgear however there is no such material to support arc burning, which is why arcs in residential wire and switchgear are not comparable in every way.

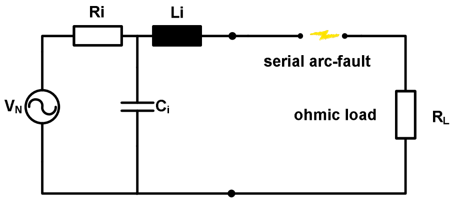

Figure 1: Supply grid with ohmic load and arc fault in series to the connected load. Arc current is limited by the connected load and therefore always within the rated current of the switchgear. R_i, L_i and C_i are equivalent elements of the of the feeding network.

Parallel arc fault

Since the air gap between the phases is usually large enough to prevent any arc ignition, parallel arcs must be initiated by somehow bridging two phases and are therefore very often an effect of external influences, for example maintenance work. Very often parallel arcs are close to short circuits with arc currents in the range of the short circuit current. There is still a chance for arcs to burn with arc currents in the range of the rated current of the circuit breaker. Reasons are contaminants, polluted insulators, or circumstances which minimize the insulation strength between the busbars. Generation of artificial arcs and measurement results have been discussed in detail in previous papers [3] and are not described here. The main differences to series arc faults are that the arc current is not limited by the load impedance and the larger arc gap [see figure 2]. The arc current will usually be higher than with series arc faults.
Voltage can be up to 400 V for arcs between two phases. Due to the larger arc gap compared to series arcs, the arc is burning more constant and has the potential to migrate between the busbars. It is possible to get a short circuit out of a parallel arc if the remaining insulation degrades.

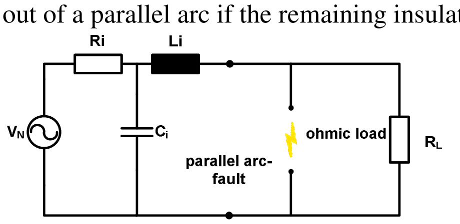

Figure 2: Supply grid with arc in parallel to connected ohmic and inductive load. Overall current is sum of arc current and load current, which superimposes all arc characteristics.

ARC CHARACTERISTICS IN THE TIME DOMAIN

The principal characteristics of an AC-arc are quite well known [4]. Arc characteristics are mainly influenced by applied voltage, gap distance, electrode surface and line impedance [5, 6]. Since tests in this paper were only done for low voltage switchgear, the voltage level is limited to 230 V or 400 V phase to phase. In the time domain, the most obvious characteristic of an AC arc is arc extinguishing after current zero. This was found for all voltage levels and is a well known phenomenon.

Gap in the arc current due to extinguishing arc

During the time between arc extinguishing and re-ignition there is a current-gap. Its duration depends mostly on gap distance and on the condition of the plasma between the electrodes. If the plasma is already in a state of low resistivity because of previous arcs, it is more likely to have shorter gaps in arc current. The bigger the gap distance between the electrodes, the higher the arc voltage and the recovery voltage has to rise to higher values to re-ignite the arc [see figure 3]. This especially happens with parallel arcs because the arc can burn undisturbed between two phases or phase and ground.
Load inductance also has an effect on the duration of the current gap. Highly inductive loads reduce the duration of the gap in current and the slew rate of the current after re-ignition. Whether the gap is still visible strongly depends on the ratio between arc resistance and load inductance [7]. The higher the arc resistance compared to the load inductance, the lower is the influence of the connected inductive loads, for example a large motor in the circuit.
With series arcs, the arc gap is quite smaller. After several arcs it is possible that the generated heat melts enough copper to enlarge the gap, or the busbar begins to bend and in this way separate more and more from each other. Also, because the electrodes in the form of the overlapping busbars have a large surface, the arc plasma is cooled down and heat can be dissipated quite fast. This influences the re-ignition voltage of the following arc. The low distance makes it possible for molten copper to form small bridges between the electrodes. These bridges form electrical connections for a short time. Because of their small cross-section, the ampacity is too low to carry the arc current. Small molten copper drops may bridge the gap distance of the previous arc and there may be no time-lag after current zero in some of the half-cycles [8]. In figure 4 the current shows gaps at several current zero crossings. There are also current zeros, where the current flow is not interrupted (as ahead and after the third positive half-cycle). A gap in arc current is not a constant phenomenon for series arcs.

Steep current edge due to re-igniting arc

After the arc has extinguished, it takes a certain time until the voltage rises high enough for the arc to re-ignite. This process produces a steep current edge. The slew rate and duration of this edge depend on the duration of the current gap and on the connected load. In case of series arc faults, this process is very unstable.

Tests in a laboratory setup showed that arc re-ignition strongly depends on the grade of surface oxidation. For low oxidation the poor contact region could be bridged by molten copper and prevent re-ignition. The tests also showed that for higher rates of oxidation it was more likely to have arc extinguishing at current zero and re-ignition. This may be a result of the higher surface resistivity due to the thicker layer of copper oxide.

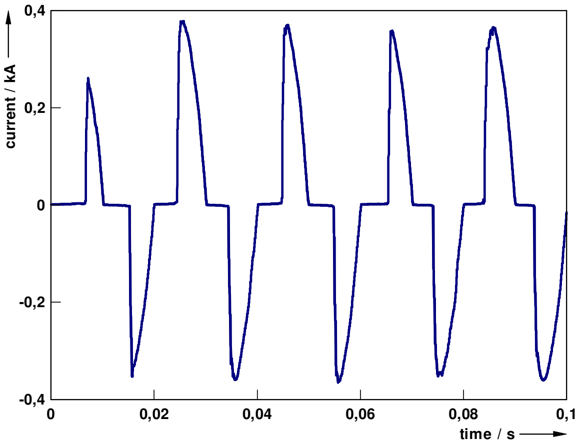

Figure 3: Current of a parallel arc between two phases. Arc current is limited by a resistor (approx. 1.4 Ω). Arc ignition was initiated by a small metal film resistor.

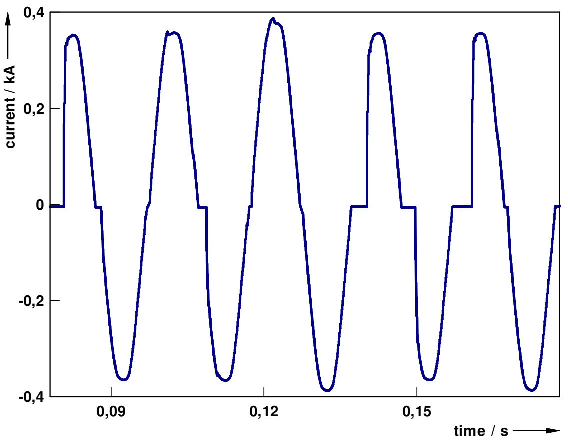

Figure 4: Current measurement of series arc fault. The current has gaps because the arc extinguishes after zero crossing. Due to molten copper, sometimes a conductive bridge forms, which prevents current interruption and arc re-ignition (like after the third positive half-wave).

Conclusions on arc characteristics in the time domain

If there is no arc re-ignition because of molten copper connecting the defective busbars, it is very difficult to distinguish the fault from a well connected busbar. The non-stable characteristic of arc extinguishing and re-ignition makes it quite difficult to reliably detect a series arc, especially if the load in series to the defective busbar has a high impedance.

For parallel arcs this is much easier. The duration of the current gap is longer and occurs continuously after every current zero. Also the arc current is only limited by surface conditions of the failure region and the electrodes. Therefore, the arc current might be much higher for parallel arcs than for series arcs. The arc current and its characteristics are more stable and well defined. This can be used to detect such a failure more reliably.

ARC CHARACTERISTICS IN THE FREQUENCY DOMAIN

To identify arc characteristics on measured currents, the spectral analysis with the FFT (Fast Fourier Transformation) is a powerful tool. For the FFT used with the measured data, the MATLAB Fourier transformation function was used. It delivers the spectral magnitude of the measured current in the frequency domain. The diagrams presented in this work show the relevant characteristics in the frequency domain.

Elevated third harmonic

Several papers investigating the topic of arc faults already mentioned the third harmonic as a relevant indicator for an arc [9, 10 and 11]. The elevated 3rd harmonic at 150 Hz was also found in the measurements of series and parallel arcs. Especially for parallel arcs the third harmonic is remarkably high. This can be an indicator for an arc fault. Since the harmonics are also influenced by normal loads, it is very dangerous to only rely on the amplitude of the third harmonic. The 3rd, 5th and 7th harmonic are especially influenced by current converters.

Elevated frequency spectrum up to 2 kHz

The spectral current amplitude is elevated through the whole spectra from 100 Hz to 1.5 kHz. Usually this area is dominated by the level of single harmonics. The spectral amplitude of interharmonic frequencies is usually much lower. In case of an arc fault this is very different. The spectral current amplitude of these interharmonic frequencies is also increased because the arc fault is a broadband signal with a temporal jitter in the arc re-ignition. This characteristic can be a strong indicator for an arc fault (see middle section of figures 5 and 6).

Elevation in the spectral magnitude in the range of 2 to 5 kHz

In the range of 2 to 5 kHz the arc current spectrum is slightly increased and almost forms an elevation. These frequencies are caused by the rising current edge after arc re-ignition. This edge is quite steep with rise times from 10 to 100 µs. For parallel arcs the spectral amplitudes in this area are higher because of the longer gap time until arc re-ignition. The current has to rise higher than for shorter current gaps. With series arcs this elevation is not so significant. Current is not always interrupted after current zero crossing, so the re-ignition and thus the steep current edges are not present in every half-cycle.

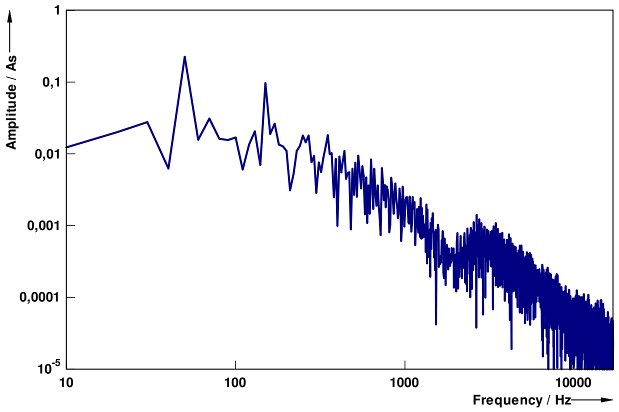

Figure 5: Spectral analysis of parallel arc fault. Highest peak is 50 Hz. The 3rd Harmonic is comparable high. The current level is elevated over the whole frequency spectrum from 100 Hz to 10 kHz. The remarkable area between 2 kHz and 5 kHz is a result of the steep current edge because of arc re-ignition.

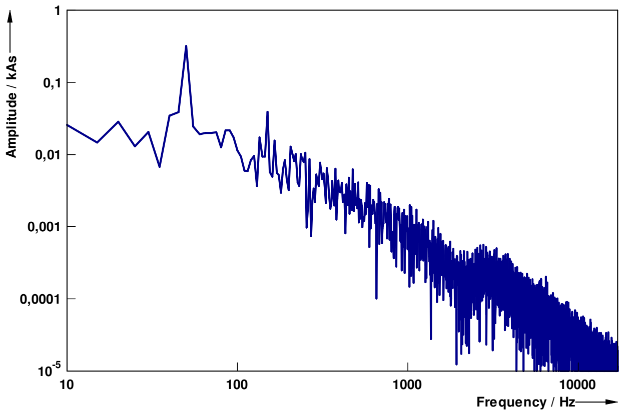

Figure 6: Spectral analysis of series arc current. Highest peak is the 50 Hz net frequency. The spectrum is comparable to the spectra of parallel arcs. The 3rd harmonic is less increased due to the shorter gaps in the arc current after zero crossing.

CONCLUSIONS

The purpose of this paper is to show characteristics of series and parallel arc faults in low voltage switchgear. For this purpose arc currents were artificially generated in the lab. Although it is not possible to generate an arc which represents all possible types of arcs, it is possible to identify several areas in the time and frequency domain which are significant and common for almost all different kind of arc faults and thus can be used to detect most arc failures. It is evident that more than one criterion and characteristics have to be used for the safe and reliable detection of a real arc fault event occurring in service. Otherwise it will be possible that special load current signals (current converters or soft starters) will cause a false detection and tripping of the circuit breaker.

- Characteristics of arc faults could be found especially in the frequency domain. The spectral current amplitudes of interharmonic frequencies are significantly higher in case of arc currents.
- Since every arcing event has different amplitudes, it is difficult to set a certain threshold level for a specific spectral current density in order to detect an arc fault. If the arc current is very low compared to the other connected load currents, the detection of arc faults becomes more difficult.

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