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FAST FAULT DETECTION FOR POWER DISTRIBUTION SYSTEMS

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ABSTRACT

This paper discusses aspects of fault detection for power systems which require fault removal before the first peak current after the initiation of a short circuit fault. Firstly, speed of fault detection is discussed and in particular how “fast” fault detection should be interpreted in this paper. Secondly, apparatus that would benefit from fast fault detection is described and in what kind of power systems it could be used. Finally, algorithms appropriate for use in fast fault detection are discussed and analysed in a case study with respect to fault current levels, and requirements for fault detection equipment including detection time and sampling rate.

KEY WORDS
Fast fault detection, industrial system, current limiting

1 INTRODUCTION

The use of terms like “fast” fault detection when discussing the speed of fault detection has shown to be quite subjective and not always referable to a specific time. In this paper, the term “fast fault detection” is defined based on the ability to provide current limiting devices with information on the fault so that the fault current can be limited or removed before the first peak of the fault current has occurred. Furthermore, algorithms to estimate system parameters such as voltage and currents based on a few samples of measured data are presented and analysed in a case study with respect to detection time and sampling rate.

2 FAST FAULT DETECTION

When discussing the speed of fault detection a number of key expressions are commonly used such as:

- High-speed relay, defined by IEEE standard [1] as: “A relay that operates in less than a specified time. Note: The specified time in present practice is fifty milliseconds (three cycles on a 60 Hz basis)”
- Fast fault detection, commonly used for fault detection within a period of power frequency but sometimes used for fault detection as fast as 40 microseconds [2].
- Very fast fault detection, commonly used for fault detection within half a period of power frequency but sometimes as fast as a few milliseconds [3].
- Ultra high speed relaying, commonly used for fault detection within a quarter of a cycle. Often implemented to detect the travelling waves caused by the fault in EHV or UHV overheadlines [4].

For this paper fast fault detection is defined as “fault detection for systems that require fault removal or limitation before the first current peak after the initiation of the short circuit.” Allowing for an apparatus operating time of a few milliseconds that leaves around one millisecond for the fault detection.

3 CURRENT LIMITING CONCEPTS

Power circuit breakers intended for interrupting alternating currents normally have an interrupting principle such that the current can only be interrupted when they pass through the natural zero crossings twice per period. With such breakers it is not possible to remove or limit the first current peak after the initiation of the short circuit. Even if the fault is detected in the same instant as it is initiated, the fault will persist for about half a period. Recent techniques have, however, made it possible to develop apparatus which has the ability to limit this first current peak.

3.1 Current limiting devices

Current limiting devices can limit or interrupt currents without relying on the natural zero crossings. A well-proven concept [5], namely the Is-limiter, relies on a current limiting fuse that limits and interrupts the current in a few milliseconds after the initiation of a short circuit. The Is-limiter has the disadvantage that once the fuse has melted it has to be manually replaced before the Is-limiter can be put into service again.

Other concepts without that disadvantage have been proposed by Ekström et al [6], who have studied a current limiting device based on power semiconductors. The operating time of that particular concept is also a few milliseconds.

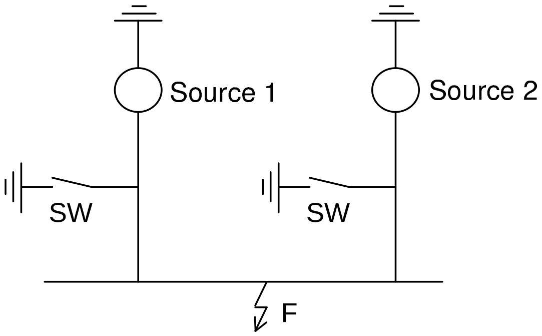

Figure 1. The current diverter principle

Concepts utilising superconductive materials have also been proposed [7].

3.2 Current diverter concept

A current diverter principle has been studied where the fault currents are not really limited but instead diverted to earth. When a fault is detected a switch is operated, closing the current path to earth at one or a few specified locations. The concept is illustrated by figure 1 which shows a power system fed from two sources.

A fault at location F would cause fault currents flowing from both sources. Once the two switches (SW) have closed the current paths to earth, no current will flow through the faulted point but instead through the two switches. The currents are interrupted at the source by a standard circuit breaker. When the switches are made sufficiently fast and with fast fault detection, the current at the faulty busbar will never reach the first current peak of prospective fault current. Originally the concept was developed to detect and extinguish open arc faults within a switchgear [8], but the principle works equally well even with solid faults.

4 BENEFITS OF FAST FAULT DETECTION

Generally, the longer a fault is allowed to persist, the worse are the consequences. At the fault location, an arcing fault could cause extensive damage, but even in remote parts of the system, it might give rise to a voltage dip, causing sensitive equipment to fail. Thus, the shorter the fault detection time, the less serious the consequences.

Fast fault detection is a prerequisite for the fault limiting or fault diverting concepts previously mentioned. Using these concepts, a power system can be operated under conditions not otherwise allowed.

4.1 Connected systems

The greater flexibility and higher short-circuit power gained from connecting two power systems cannot always be achieved due to large short-circuit currents. These currents could exceed the requirements of the apparatus installed in the systems such as circuit-breakers, transformers, cables, and overhead lines. The Is-limiter has traditionally been used to make the connection possible. For this case other technologies described in section 3 could also be used.

4.2 Expanding systems

Distributed generation such as windpower or local generators can often be troublesome to add to an existing system due to the increase in short-circuit power. When a power system is operated at the limit of its capacity with respect to available short-circuit power it can be a major cost adding new generation due to the required strengthening of the power system apparatus. If a current limiter or a current diverter concept is applied to the system it will be able to add new generation without the disadvantage of higher short-circuit currents, which are either limited or diverted to earth at a safe location.

5 ALGORITHMS

The aim of the fast fault detection algorithms is to determine from measured voltage and current samples whether a fault has occurred in the power system or not. The sampled measurements are first processed to form an estimate of the actual voltage or current in the power system. The estimated voltages and currents are then compared with a fault criterion, which for example can be the current magnitude or the apparent impedance.

There are numerous methods to estimate the voltages and currents [9]. Some use a few samples, which are fitted to a waveform model or a system model. Others use samples taken over a whole period for the waveform model fit.

The challenge of fast fault detection is to use as few samples as possible but still providing enough information.

As a first approach to fast fault detection two methods using three and four samples respectively are described in this section, and their performance with respect to sampling rate and level of detection is evaluated in a case study in section 6.

Computation time is not considered to be a limitation for these two algorithms.

5.1 Estimation of current magnitude

Phadke and Thorp [10] describes an algorithm for estimation of current or voltage magnitude and phase based on three consecutive samples. The algorithm fits the samples by a least square error approach to a sinusoidal of fundamental frequency.

If i_1, i_0 and i_{-1} denote three consecutive samples, the estimated magnitude is given by:

$$|I| = \sqrt{I_c^2 + I_s^2} \tag{1}$$

where

$$I_c = \frac{i_1 \cos\theta + i_0 + i_{-1}\cos\theta}{1 + 2\cos^2\theta},$$

$$I_s = \frac{i_1 - i_{-1}}{2\sin\theta}$$

and θ is the fundamental frequency angle between samples $\theta = 2\pi f_0 \cdot \Delta t$, where f_0 is the fundamental frequency and Δt is the time difference between two consecutive samples.

5.2 Estimation of apparent fault impedance

Johns and Salman [9] describe an algorithm for estimation of apparent impedance to a fault based on three (or four) consecutive samples. The algorithm fits the samples by solving a differential equation, modelling the protected object as a resistance in series with a reactance.

If i_2, i_1, i_0, i_{-1}, u_1, and u_0 denote the samples, the estimated impedances are given by:

$$R = \frac{u_0(i_2 - i_0) - u_1(i_1 - i_{-1})}{i_0(i_2 - i_0) - i_1(i_1 - i_{-1})} \text{, and} \tag{2}$$

$$L = 2\Delta t \frac{i_0 u_1 - i_1 u_0}{i_0(i_2 - i_0) - i_1(i_1 - i_{-1})} \tag{3}$$

6 CASE STUDY

Wikström [11] studied the connection of a local generator at an industrial plant in southern Sweden. One of the conclusions was that the fault current levels after the connection of the generator would exceed the ratings of the equipment installed in the power system, hence demonstrating the need for a fault current limiting concept. The same power system is used here for a case study to show how the suggested algorithms can be used for fast fault detection in an industrial power system.

It can be noted that there are several possible configurations of electronic current limiting devices and current diverters that can be used in this case in order to protect the 10.5 kV busbar, but all these concepts need fast fault detection.

6.1 Description of the system under study

Figure 2 contains a single-line diagram of the system under study. For this study, the circuit breakers indicated by squares represent either a current limiting device or a current diverter concept. The equipment within the dashed box represents the possible connection of the local generator.

Fault	Maximum fault current
in the 135 kV system	41 kA_p
in the 10.5 kV system	136 kA_p
in the 0.4 kV system	1.3 kA_p

Table 1. Maximum fault currents in the 10.5 kV system

6.1.1 Without the generator

The power system without the local generator is fed by three overhead lines at the 135 kV level. A power transformer rated at 55 MVA steps down the voltage to 10.5 kV. The load at the 10.5 kV level consists of transformers, motors and capacitor banks. For this study, the load is lumped into an impedance load, which at the rated voltage of 10.5 kV corresponds to a load of 16 MVA. The impedance model has been calculated by Wikström [11] and adjusted to real measured values at the plant. Furthermore, a transformer rated at 1.5 MVA steps down the voltage to 0.4 kV.

The 10.5 kV system has a short time current rating of 25 kA (RMS-value), which it will withstand for 1 second. Due to a decaying dc-component in the short-circuit current, the first current peak will be higher (rated at 2.5xRMS-value according to standards) than the current peak corresponding to the RMS-value ($\sqrt{2}$xRMS-value).

6.1.2 The generator

The generator is rated for 81.25 MVA at 10.5 kV and is driven by a gas turbine supplied with excess gas from the steel process.

6.1.3 Application of faults

Faults applied at three different fault locations have been studied. Three phase-voltages have been measured on the 10.5 kV busbar and three phase-currents have been measured in the feeder between the 55 MVA transformer and the 10.5 kV busbar to provide data for the algorithms under study. The algorithms are applied for all three phases simultaneously.

6.1.4 Maximum fault currents

Maximum fault currents for the three fault locations have been calculated, and are summarised in table 1. The currents are measured in the 10.5 kV system and expressed as peak values.

The rated peak value of the 10.5 kV system is 62.5 kAp. Hence, it can be concluded that whenever a fault occurs within the 10.5 kV system, it must be detected fast enough, giving a current limiter or a current diverter time to operate. Faults at the 135 kV level or the 0.4 kV level

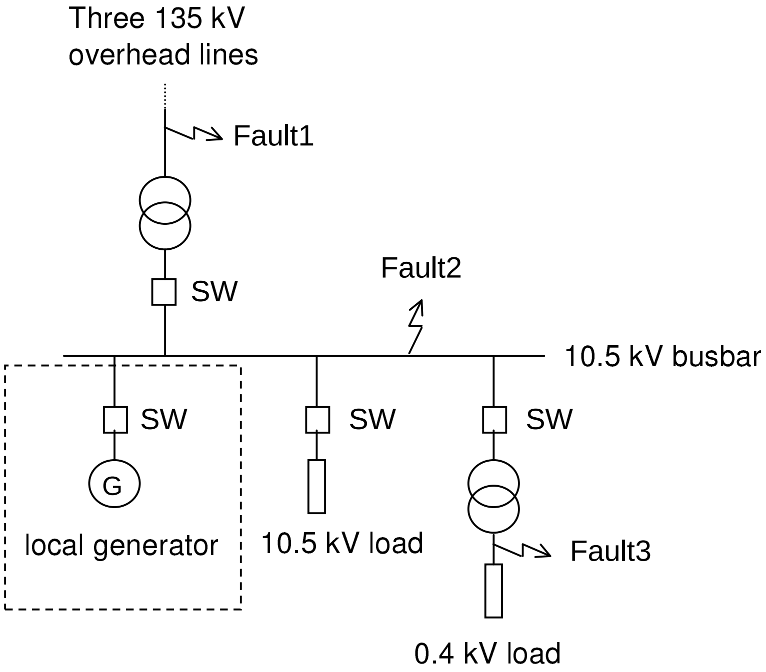

Figure 2. The power system under study

lead to fault currents in the 10.5 kV system that are within the ratings of the system, hence allowing more time for the fault removal.

In the case of a current limiter application another consideration is that when voltage dips occur at the 135 kV voltage level, the generator will feed power to the 135 kV system, thus mitigating the voltage dip as measured at the 10.5 kV level. This particular study showed that the maximum current supplied by the generator at such a voltage dip was 10 kAp.

6.2 Requirements on fault clearing time

For the case study, the maximum fault current in the 10.5 kV system has been shown to exceed the rating of the system excessively when the generator is connected. Hence, as Wikström [11] pointed out, the system must either be rebuilt or be equipped with apparatus that removes or limit the current before the first current peak. The rated peak current of the system is known (62.5 kAp) and the time for the short-circuit current to reach 62.5 kAp has been calculated for a number of fault inception angles. The worst case scenario is found to be 2.8 milliseconds. Allowing for an operating time and a safety margin of altogether 2 milliseconds for the fault removal apparatus leaves 0.8 milliseconds for the fault detection.

6.3 Fast fault detection algorithms

A number of calculations have been performed to estimate the current magnitude when a fault occurs, using the equations of section 5.1. The sampling rate, fault inception angle and the detection level, i.e. when the magnitude of the current exceeds a set value corresponding to a fault in the system, have been varied throughout the calculations and their effect on the fault detection time evaluated. When setting the detection level in the range 2.5-6.5 times the pre-fault current in the branch between the 55 MVA transformer and the 10.5 kV busbar, it is possible to reach a detection time of just about 3 ms with a sampling rate of 1 kHz, a detection time of just about 1.5 ms with a sampling rate of 2 kHz and a detection time of 0.75 ms with a sampling rate of 4 kHz. Hence, for this case study fast fault detection can be achieved based on monitoring the current magnitude.

However, to be able to distinguish a fault in the 10.5 kV system from a fault in the 135 kV system, some kind of directional criteria must be used. Otherwise, a fault in the 135 kV system would operate the current limiter or diverter even though the 10.5 kV system can withstand such a fault. The second algorithm proposed (equations from section 5.2) can provide such a directional criterion. For faults within the 10.5 kV system the apparent resistance and inductance will always be positive whereas a fault in the 135 kV system will yield negative apparent resistances and inductances. Faults in the 0.4 kV system correspond to much higher apparent resistance and inductance than the other two fault locations. Hence, it is possible to distinguish a fault in the 10.5 kV system from a fault in the 0.4 kV and the 135 kV systems by measuring the voltage and current at a single location.

7 CONCLUSIONS

This paper starts by discussing terms related to the speed of protection, and “fast” fault detection is defined. Two algorithms possible for fast fault detection are given and applied to a case study. It has been shown that these simple algorithms can provide fast fault detection.

However, the effect of noise on the algorithms remains to be studied. Noise is interpreted as harmonics and measurement errors for example, but also as transients that can occur in a power system during regular service conditions such as switching transients.

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