FAST FAULT DETECTION FOR PEAK CURRENT LIMITATION BASED ON FEW SAMPLES

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ABSTRACT

This paper begins with a motivation why “fast fault detection” is an important topic. Two particular apparatus for which their operation requires “fast fault detection” are briefly described. An algorithm using instantaneous sampled current values to detect faults is described and evaluated by computer simulations with the aid of EMTDC – a computer program for performing dynamic calculations/simulations of power systems. It is demonstrated that a three-phase fault can be detected within approximately 1 ms after fault inception. Power system transients such as capacitor energization and transformer energization could cause unintentional fault detection of the algorithm, but it is shown that a capacitor energization can be discriminated from a fault by lowpass filtering the current before it is sampled. Furthermore it is shown that transformer energization can be discriminated from a fault by using the current differential between two samples as a conditional requirement.

INTRODUCTION

As discussed in [1], the expression “fast fault detection” is not defined in an exact manner, which was exemplified by analyzing how the expressions “high speed relay”, “fast fault detection”, “very fast fault detection”, and “Ultra High Speed relay” were used and what they meant. In this paper “fast fault detection” is to be interpreted as fast enough to allow fault clearing or fault limitation before the first peak of the prospective fault current. A few applications that benefit from “fast fault detection” are given a short description below.

Arc protection systems. An arcing fault in an enclosed substation environment will, if not extinguished, lead to extensive damage and potential harm to safety against human hazard. As the arc develops the temperature will rise and in turn cause the pressure to rise. After approximately 10 ms a pressure wave will travel through the substation [2]. A pressure relief that opens when the pressure exceeds a certain threshold can to a certain extent but not completely mitigate the potential damages caused by the pressure wave. If the arc is not extinguished, it will rapidly cause severe meltdown of conductors and partitions, hence damaging the switchgear so that extensive repair or even replacement is necessary. An arc is relatively easy to detect using the light from the arc as a fault detector. The signal from the fault detector can then be used to trip the main circuit breaker thus extinguishing the arc. A typical circuit breaker has a breaking time of around 50-55 ms. The damage to the substation is then limited but some maintenance is required before the substation can be put back in service. It is possible to achieve a shorter arc extinguishing time if a bypass switch is used. The bypass switch is closed thereby short-circuiting the arc by closing a parallel path to earth. Two examples of such bypass switches are available as an Arc Eliminator [3] or an Arc Terminator [4]. Both switches operate to extinguish the arc within 5-10 ms after fault initiation, i.e. even before the pressure wave fully develops. This is achieved by short-circuiting the arc by closing a parallel path to earth. At the same time the main circuit breaker is tripped and finally interrupts the fault current (which now flows through the parallel path to earth). When using an Arc Eliminator or an Arc Terminator, the substation can be put back in service after inspection. The damage is virtually zero.

Current diverter systems. It is possible to use an arc extinguishing system even though a fault is non-arcing or if the fault is outside the substation thus making it difficult to detect using the light from the arc. A system that detects faults by analyzing power system current and/or voltages could replace the light detector when the light is not available or ambiguous. The light detection system operates within 1 ms after arc initiation and the fault detection system based on analyzing power system signals must perform in a fairly comparable time. The reason for short circuit non-arcing faults is to transfer the fault current from a random, potentially dangerous fault location to a controlled path to earth. If the bypass switch could be closed before the first current peak of the prospective fault current it could be used to protect sensitive parts of the power system from the mechanical forces caused by the peak current, thus providing a similar functionality as a fault current limiter.

Fault current limiters. A fault current limiter is an apparatus that can limit the prospective fault current before the first current peak is reached thus protecting the power system from high mechanical forces. There are fault current limiters based on numerous principles such as super conducting fault current limiters [5] and power semiconductor based fault current limiters [6]. Such

1 Approximately 5-10 ms after fault inception.
devices also require fast fault detection (even though the super conductive fault current limiter is operated by the fault current itself). These examples demonstrate the need of fast and reliable fault detection for power distribution systems.

METHODS

Theory

Instantaneous values. A straightforward method to detect a fault is to use the instantaneous value of the sampled current and determine that a fault has occurred when a certain level has been exceeded. However, any error in the data acquisition system or a power system transient could give a single current value higher than the trigger level, thus causing a false detection. To make the fault detection less sensitive to random instantaneous current values above the trigger level a technique similar to the fault type classifier described by Phadke and Thorp [3] is used. Phadke and Thorp uses the fault type classifier to determine which phase(s) that possibly is faulted and performs further calculations on that phase(s) to lighten the computational effort. No trip signal is based solely on the fault type classification scheme. In this paper the fault type classifier is used to detect a fault and a trip signal will be issued if the threshold is exceeded. Furthermore, a higher sampling frequency is used in this paper.

The algorithm can be described as:

(i) Set the counter to 0
(ii) Measure the current.
(iii) If the absolute value of the current is larger than the trigger level increase the counter by 1. Otherwise decrease the counter by 1 (unless the counter is 0).
(iv) If the counter is equal to 5, issue a trip signal.
(v) Repeat from (ii).

A sampling frequency high enough to allow fault detection within 1 ms will be selected.

Derivative. Power system transients such as capacitor energization or transformer energization could give rise to current values over the trigger level even though no fault has occurred. Sometimes it is possible to increase the trigger level to make sure that capacitor energization is not detected as a fault. If it is not possible to raise the trigger level, the derivative (throughout this paper, the derivative is always assumed to be taken with respect to time if not otherwise stated) of the current can be used as a conditional fault detector so that the trip signal is only given at the same time as the derivative is above a certain level. For high sampling rates, it might be numerical difficulties to calculate the differential since the division with a small time step \( \Delta t \) will magnify possible errors in the sampled signal. The differential current in-between two time steps (\( \Delta i = i(t + \Delta t) - i(t) \)) will be used instead of the derivative to avoid some of the numerical difficulties. A study of the differential in case of a fault will be compared to the differential when energizing a capacitor and a transformer to determine whether the differential can be used to discriminate between the three events.

Filter. Capacitor switching can produce high inrush currents with high derivatives. The inrush current however is not of fundamental frequency but of higher frequencies determined by the inductance and capacitance of the actual circuit. If it is not possible to discriminate a capacitor inrush current from a fault current by using the derivative, a low pass filter can be applied before using the instantaneous samples. The anti-aliasing filter in the data acquisition system is a low pass filter that makes sure no frequencies above half the sampling frequency is in the signal to avoid erroneous result when reconstructing the signal (Nyquist). However, since it is desired to use a high sample rate so that the time for five consecutive samples to fall above the trigger level is small, the anti-aliasing filter determined by the sampling frequency will let through much of the capacitor-switching transient. To filter the capacitor switching transient a low pass filter with a cutoff frequency of a frequency that will be determined will replace the anti-aliasing filter. It must then be made certain that the sampling frequency always is larger than twice the cutoff frequency of the low pass filter to avoid aliasing.

A low pass filter introduces a phase delay that also must be accounted for when studying the fault detection time. The phase delay grows larger as the cutoff frequency is decreased. Once a cutoff frequency is determined it must be verified that the phase delay is not too large so that the fault detection takes more than 1 ms.

Combined methods. The algorithm described above is not directional. If the power system contains two sources (as for example a local generator), high currents may flow in the system for faults outside the protection zone that not shall be detected as a fault. In [1] the application of an algorithm that uses four consecutive samples to form an estimate of the impedance of the protected object is described. Such an algorithm has directional properties but is sensitive to errors in the sampled signals if the sampling rate is selected to high. For that particular study, the estimated impedance was reasonable at a sampling rate of 4 kHz. At that sampling rate it is possible to calculate an estimate of the impedance in less than 1 ms. If the two methods are combined, a fast directional algorithm is obtained. Since no trip is issued unless both algorithms detect a fault, the directional algorithm can be allowed to be sensitive.

The extension of the algorithm can be described as:

(i) Down sample the signal to 4 kHz.
(ii) Estimate the impedance of the protected object.
(iii) If a fault is detected inside the protection zone, and if the first method has produced a trip signal, forward the trip signal as an output of the algorithm.
Case Study

The algorithm described above has been implemented and tested in EMTDC – a software for dynamic calculation and simulation of power systems. Two power systems have been simulated to test the algorithm. The first power system is based on standard values of nominal voltages, load currents and short circuit currents given by the IEC (International Electrotechnical Committee). The second power system models a part of a distribution system at a Swedish steel plant. The data of the respective system are as follows:

System 1: The system voltage is $U_h = 12$ kV, the load current is $I_n = 630$ A, and the short-circuit current is $I_k = 40$ kA. To be able to study a few power system transients, a capacitor rated at 4.08 MVAr at 12 kV and a transformer rated at 102 MVA at 12 kV have been added to the system. The proposed algorithm has been implemented as a user-defined component, which takes a phase current as input and gives a trip signal as output. The trip signal is zero when no fault is detected and one if a fault is detected (i.e. the counter have reached five). The differential $\Delta i = I(t+\Delta t)-I(t))$ is also recorded at the time that the trip signal is given to be able to investigate if it can be used to discriminate between a fault current and other power system transients. Furthermore, a low pass filter has been added to the system to be able to separate between capacitor energization and a fault by using the instantaneous filtered current values. Short circuits, capacitor energizations, and transformer energizations have been simulated to determine whether the algorithm can discriminate between a power system fault and a power system transient.

System 2: The power system selected for the study is part of a large distribution system at a Swedish steel plant (SSAB Oxelösund). The steel plant is supplied by three overhead lines at 135 kV. The investigated subsystem is at the 10.5 kV level. The system voltage is $U_h = 10.5$ kV, the load current (implemented from actual measurements) is $I_n = 840$ A, and the short-circuit current from the feeding transformer is approximately $I_k = 25$ kA. Apart from steel the steel plant also delivers excess process gases to a generator installed in the local grid. Wikström et al have studied the possible reconnection of the generator to a more suitable location in the grid in combination with a fault current limiter [8]. As already mentioned fast fault detection is required for fault current limiting apparatus, thus this case study uses the same power system as that Wikström studied. The generator is rated 81.25 MVA at 10.5 kV. The model also contains part of the 130 kV as well as the 0.4 kV system to be able to study how faults at those voltage levels influence the current and the fault detection at the 10.5 kV level. The same user defined components as in system 1 were implemented and since the power system contains two sources, the directional algorithm was also included.

RESULTS

System 1: The trigger level was selected to 3 times the nominal load current (typical settings of an overcurrent relay lies within 2.5 – 6 times the nominal load current according to an experienced relay protection engineer). The fault type classifier was implemented in EMTDC and three power system events were simulated. The three-phase fault was correctly detected and when the sampling frequency was selected to 10 kHz, the detection time was never more than 0.5 ms for a wide range of fault initiation times corresponding to a complete power frequency period. However, both the transformer energization and the capacitor energization also produced a trip signal. Investigation of the sampled data signals revealed that it would be quite easy to raise the trigger level to avoid erroneous trip signals for this particular case and still be able to detect faults within 1 ms. However, for systems were it is not possible to raise the trigger level other solutions must be tried. First the differential of the current was investigated. The differential between the current value when the trip signal was issued and the current value one sample earlier was compared for the fault current, the capacitor energization and the transformer energization. It turned out that it is possible to discriminate between a fault and transformer energization by using the differential but not between a fault and capacitor energization. A low pass filter was added to the simulations. A second order Butterworth filter with a cutoff frequency of 300 Hz was suitable for this study. Now it was possible to discriminate between a fault and the capacitor energization. With nothing else changed the detection time was now 1.0 ms and the simulated fault was the only power system events for which a trip signal was issued. Figure 1 contains a plot of the prospective fault current in one phase, the limited fault current due to the fault diverter operation, and a scaled trip signal which becomes 1 once a fault is detected.
The capacitor energizing was discriminated from a fault by low pass filtering the signal and the transformer energization was discriminated from a fault by using the current differential. The phase delay of the filter was estimated by investigating the sampled signals to approximately 0.75 ms.

**Conclusion:** For this particular study it was demonstrated that it is possible to discriminate between a fault, capacitor energization and transformer energization by using a combination of low pass filtering and by using the current differential between two samples.

**System 2:** To determine an appropriate trigger level, three phase faults were first simulated at the 0.4 kV level for different fault inception angles. The maximal current measured in the 10.5 kV system was 1.75 kA, which is approximately 1.5 times the peak current of the nominal load current. Thus it can be concluded that the trigger level can be set to 3 times the nominal current for this system also.

The same power system events as for system 1 was simulated. First without the filter and then with the filter included. For faults at the 0.4 kV level no trip signal was issued but for faults at the 130 kV level a trip signal was issued. The calculation of apparent impedance was now added to the simulation and the trip signals of the two algorithms was connected in series so that a trip signal was issued only if both algorithms detected a fault. The fault type classifier detects fault both in the 130 kV and in the 10.5 kV system whereas the impedance algorithm can distinguish between faults at different voltage levels (or at least if the fault is upstream or downstream as seen from the measuring transformers). The simulations showed that it is possible to select trigger levels so that fault detection is possible within 1 ms and so that faults at the 130 kV level does not produce a trip signal.

**DISCUSSION**

**Conclusions**

The algorithm based on instantaneous values is capable to detect a three-phase fault within approximately 1 ms after fault initiation. Two-phase faults were not tested in this study but it is the authors belief that the algorithm will be able to detect two-phase faults also. It is possible to separate a capacitor or transformer energization by including a low pass filter and analyzing the differential of the current. For power systems that contains several sources directional properties is required. If a well-known directional algorithm (applied at a higher sampling rate than usual) is paralleled with the algorithm described in this paper a fast and directional fault detection is possible.
Considerations

Capacitor and transformer energization are not the only transients in a power system. Computer speed is not considered an issue at a sampling rate of 10 kHz. Modern computers or signal processors will have plenty of time to perform the necessary calculations in between samples.

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LIST OF REFERENCES


