A New Method of Line Differential Protection Enhanced by Using Incremental Currents

Zhanpeng Shi*, Ivo Brncic*, Youyi Li †

* ABB, Substation Automation Products, Sweden, † ABB, Corporate Research Center, Sweden

Keywords: Protection of power lines, differential protection, adaptive differential protection, incremental currents.

Abstract

The classical differential protection may mal-operate during severe external faults due to the saturation of current transformers. To overcome this problem, a new solution of line differential protection is proposed based on the use of incremental currents, i.e. the current changes due to the fault. By comparing the relative angle of incremental currents, a reliable decision can be made whether the fault in a phase is internal or external. Based on the fault information, the sensitivity and security of classical differential protection can be greatly improved at the same time.

1 Introduction

The line differential protection is normally applied as the primary protection for the transmission lines because of the inherent selectivity and high sensitivity. To improve the reliability of the function, some existing power line differential protections apply a negative sequence current based internal/external fault discriminator [1]. That is a good and reliable solution to determine internal or external faults even with in-line power transformers with their inherent phase shifts included in the zone of protection. Unfortunately such an internal/external fault discriminator is not phase selective. In case an external fault occurred in one phase and a simultaneous internal one occurred in another phase, the negative sequence current based internal/external fault discriminator could be confused and gave uncertain fault information.

Another challenge for the classical line differential protection is the stability during external faults. The false differential currents may occur due to CT saturation or measurement errors. The severe CT saturation can create big enough false differential current which cause the differential protection mal-operate. Some addition features, such as harmonic blocking, can be used to maintain the stability during external faults. However, it may slow down the operation of internal faults and not always reliable for the external faults when the false differential current are caused by DC components in the fault currents without very much harmonic distortion.

Those challenges for the classical differential protection can be improved with the proposed solution by using the information from incremental currents, i.e. the sudden current changes due to the fault. By a comparison of the relative angles of the incremental currents at both (or all) ends of the protected power line, a reliable decision can be made whether the fault in a phase is internal or external. Based on this very reliable information, the protection can be made faster for internal faults, and more secure against unwanted trip commands for severe external faults with CT saturation. Nowadays it is just as important to remain stable against severe external faults as to operate correctly and quickly for internal faults. The incremental currents-based differential protection guarantees a great security, i.e. stability against external faults.

2 Incremental currents

The calculation of incremental currents is based on the superposition theorem. The measured phase current during the fault can be considered as the sum of pre-fault (load) current and incremental (fault) current [2]. In order to determine the incremental currents, i.e. the changes of the currents because of the fault, the pre-fault currents, i.e. the normal load currents must be measured at all ends of the protected circuit. These pre-fault vectors are obtained by feeding the instantaneous values of all currents (raw samples) to numerical Fourier filters, which transform the currents from the time domain into the complex domain. The result of the filtering are vectors, which represents currents with their real and imaginary components, are memorized in order to calculate the average values of the pre-fault load currents. This to exclude eventual minor sudden transient changes of currents for example in networks with a lot of unsteady industrial load. It is recommended that at least one or two fundamental frequency pre-fault periods are taken into account.

The average currents are calculated on-line and the incremental currents are as well calculated all the time, based on the actual average currents taken as reference. Under normal load conditions, they will be very small, or practically zero. Only if they are high enough in order to do any secure directional test, the relative angle between them is calculated. The calculation of the average pre-fault current in a phase is temporarily stopped when an internal fault in a phase is suspected. Under the suspected internal fault conditions, the average pre-fault current, expressed as a vector, is then subtracted from the actual total fault current, as well expressed as a vector. In this way, the pure fault current
components, i.e. the incremental (superimposed) currents are determined.

This averaging process is stopped already at a specific low value of the differential current, when an internal is detected and resumed when the fault has been cleared, by opening a circuit breaker or otherwise. The incremental currents are calculated under all the time with the fault. When the fault is observed to have disappeared, for whatever reasons, the differential current disappears, and the buffers are released and continue the process of calculating pre-fault currents.

3 Internal/External fault discriminator

The internal or external fault is determined by comparing the relative angle of incremental currents from both ends. A reliable decision can be made whether the fault in a phase is internal or external. The principle of internal/external fault discriminator is shown in Figure 1 below:

![Figure 1: Principle of fault discriminator](image1)

For internal faults, the angle between the two vectors, the incremental currents from both sides, is 0 degrees, or close to that. A small angle greater than 0 degrees may be caused by the different characteristic angles of the source impedances of the equivalent circuits as seen on both sides of the internal fault, i.e. as seen from the point of fault, [2]. A directional test is done if the incremental currents on each side are above a certain minimum value which is 1-2 % of the rated current of the power line.

It is clear that for any external disturbance, no matter if it is a sudden change of load or an external fault, the current in the affected phase(s) will change almost equally at both ends, where the current transformers are installed. The relative phase angle between the incremental currents is in this case 180 degrees assuming the standard orientation of the current transformers in such applications. The reliable information of external disturbance is obtained quickly before any current transformer saturates and false differential currents appear as a result. Measures can then be taken in time to prevent any unwanted trip due to false differential currents. Even sudden change of normal load, with equal changes in currents on both sides of the protected power line, that cause no or very little differential current, is considered as an external disturbance and is ignored.

4 Differential protection principle

The proposed line differential protection is based on the classical differential protection with dual-slope characteristic. The characteristic is adaptively controlled by the internal/external fault discriminator, as shown in Figure 2 below [3]:

![Figure 2: Adaptive characteristic based on fault information](image2)

When the internal fault is detected, the characteristic remains at default value with high sensitivity. Meanwhile, all addition features for security, such as harmonic blocking, are disabled in order to achieve fast operation. If an internal fault is detected for a while but no start signal is issued, then a high impedance fault is suspected and the operate level will be reduced by 25% in order to trip the line for high impedance fault.

When the external fault is detected, the characteristic will decrease the sensitivity by increasing the slope ratio of the characteristic and the minimum operate level. In the proposed algorithm, the slope increases to 3 times of default value which gives enough security margin for CT saturations or other measurement errors.

Theoretically the differential protection could be based exclusively on the incremental values. In other words, both the differential and the restrain (bias) currents could be composed of only incremental currents. This would elegantly solve the problem presented by the charging currents. However, there are some practical drawbacks with such a solution. For example, the variation of pre-fault current and constant errors due to frequency deviation could affect the accuracy of operation. That is why the classical way to form total differential currents with filtered value is applied, which is more accurate and reliable against disturbance in the pre-fault currents. The new features of proposed solution are as follows:
• The three phases are totally separated, independent of each other in any respect. There are three independent differential protections, one per phase.

• The incremental currents are calculated on-line and fault information is given per phase which is totally phase-segregated compared with negative or zero sequence currents based solution. This enables the single phase tripping and speed up the operation for evolving faults.

• The operate-restrain characteristic becomes adaptive based on the fault information. This feature greatly increase the security against external faults and meanwhile provides the high sensitivity for internal faults.

• The impact of CT saturation during external fault is removed by adaptive characteristic. The internal/external fault discriminator can quickly detect the fault before the CT saturates and shifts the characteristic upwards with very high security margin. This feature completely removes the risks of mal-operation due to CT saturation during external faults.

• Since the characteristic becomes adaptive, it is difficult for people to calculate the operate level of the characteristic. In the new solution, the actual operate level for a trip is made available for the user as service values. This new feature makes the post-fault analysis more complete and thus enhances the user-friendliness of the protection.

5 Simulation verification

The verification of the proposed solution is performed with Matlab/Simulink. The model simulates a 220 kV transmission line with the length of 200 km between two sources, shown in Figure 3:

![Power system simulation model](image)

Figure 3: Power system simulation model

The position of simulated faults is shown in Figure 3. The internal fault F1 is located in the middle of the line and the external fault F2 is located outside End 2. The parameters of transmission line are as below:

- $L_1 = 0.9337 \times 10^{-3}$ H/km
- $L_0 = 4.1264 \times 10^{-3}$ H/km
- $C_1 = 12.74 \times 10^{-9}$ F/km
- $C_0 = 7.751 \times 10^{-9}$ F/km

The settings of the operate characteristic are as followings:

- $I_{breakpoint} = 1250$ A
- $I_{breakpoint} = 3000$ A
- Slope 1 = 0.4
- Slope 2 = 0.8

The characteristic is adaptively controlled by internal/external fault discriminator based on the default settings.

5.1 Internal low-resistance fault in phase L1 under normal load conditions

Example shows a case where a near zero Ohm single phase-to-earth fault (L1 – E) occurred in the middle of the line. The high fault currents caused at least one CT to saturate in app. 10 ms. By that time the trip command had already been issued, in 6 ms. Observe from the Figure 4 that the condition for trip was met in 4 ms, but two more confirmations were required for security.

![Internal low-resistance fault in phase L1 under normal load conditions](image)

Figure 4: Internal low-resistance fault in phase L1 under normal load conditions

Observe that the angle between the incremental current vectors on both ends of the line was practically zero degrees when the trip command was issued. A secure indication that the fault was internal.

5.2 Internal very-high-resistance L1–E fault under normal load conditions

This example shows a case where a high-resistance single phase-to-earth fault (L1 – E) occurred in the middle of the line. The fault current was relatively low; lower than 200 Amperes which was the value initially required to trip. But as a high-resistance internal fault was indicated by the analysis based on incremental currents and the restrain current, the
required value was lowered to 75% of default setting for a while what enabled the protection to trip. Observe even that the angle between the incremental current vectors at both ends of the power line was practically zero degrees under the fault conditions. This was as secure indication that there was an internal fault.

The analysis of the event indicated an internal high-resistance fault and sensitivity of the protection was temporarily increased. Trip request command issued in 23 ms.

5.3 Severe external fault outside End 2 under no load conditions

This example shows a case where a severe external three-phase fault occurred just outside End 2. The high fault currents pushed some current transformers into transient saturation, which gave rise to high false differential currents which could result in an unwanted trip command. However, as it can be seen in Figure 6 the security margin was great with adaptive characteristic and the value required for a trip was all the time by far greater than the false differential current. Observe as well that the angle between the incremental current vectors at both ends of the power line was initially 180 degrees, which positively indicated an external fault. The angle then due to the transient current transformer saturation changed temporarily up to 120 degrees. However, this was still a secure indication of an external fault. With the current transformer saturation fading the relative angle returned slowly towards 180 degrees.

Figure 6: Severe external three-phase fault with transient current transformer saturation

5.4 Evolving fault from external to internal in the same phase

Since the proposed algorithm is totally phase-segregated, the evolving fault occurring in different phases is not a problem for the protection to operate. Therefore, the evolving fault occurring in the same phase is simulated.

In this example an external earth-fault in phase L1 outside End 2 was cleared by another protection in 100 ms. Due to the transient overvoltage on the power line caused an internal earth-fault in the form of a flashover to earth in phase L1. Figure 7 shows that the trip command was issued in 8 ms, which is good having in mind the complicated conditions.

Figure 7: Evolving fault from external to internal in the same phase

Trip signal issued in 8 ms after the external fault was cleared and the internal initiated. Note even that the angle quickly
dropped to approximate zero degrees when the internal fault was initiated which was an indication that it was an internal fault. The internal/external fault discriminator works correctly for both external and internal fault conditions.

6 Conclusions

This paper describes a new solution of line differential protection with adaptive operate-restrain characteristic. The characteristic can be changed dynamically by the use of pure fault components of currents. Based on superposition theory, the fault component of a current (incremental current) can be calculated from the difference between the memorized mean pre-fault current and actual total fault current. By comparing the relative angle of incremental currents in a phase, the protection algorithm can, therefore, determine whether it is internal or external fault. The information on internal or external fault, makes it possible to control the operate-restrain characteristic in such a way that the protection is more sensitive and fast for internal faults and less sensitive for external faults. Several simulation cases have been done to verify the solution of new protection. The simulation results prove that the new protection operates much faster for internal faults and at the same time remains stable for severe external faults with CT saturation.

References