ADAPTIVE DIFFERENTIAL PROTECTION FOR GENERATORS AND SHUNT REACTORS

Ivo Brnčič, Zoran Gajić, Stefan Roxenborg
ABB Power Technologies AB,
Sweden

ivo.brncic@se.abb.com, zoran.gajic@se.abb.com, stefan.roxenborg@se.abb.com,

Abstract. In the article a new generator differential protection is shortly described. Some new features are illustrated. One of these is the usage of negative sequence currents. Another new feature is the processing of the DC components of the instantaneous differential currents. Both novelties make the protection of generators and particularly shunt reactors stable under conditions of external faults or external disturbances such as sudden loading.

Some more light is shed to the problems typical of generator and shunt reactor differential protection. These problems are mainly due to very long DC constants of the generators and shunt reactors. The persistent DC components of primary currents, even if relatively small, have a tendency to sooner or later drive current transformers to saturation.

An interesting real life case is then added in order to better illustrate the solution of the typical problems due to the non-ideal or non-identical current transformers on both sides of the protected object. The example shows the connection of a 400 kV shunt reactor to the power system. The solution described in the paper proves that the contradictory requirements of high sensitivity and selectivity can be met to satisfaction.

Keywords. Protection, differential protection of synchronous generators, differential protection of shunt reactors, energization of shunt reactors.

1. INTRODUCTION

Generators are the most expensive pieces of equipment in the AC power system and are subject to more possible types of trouble than any other equipment. The desire to protect against all these abnormal conditions and yet to keep the protection simple and reliable has resulted in considerable divergence of opinion on the choice of protection. The choice must be made carefully since the inadvertent operation is, particularly for great generators, as serious/expensive as failure to operate. On the other hand, failure to clear a fault promptly may cause expensive damage to the generator. Another difficulty is the fact that, unlike other equipment, opening of a breaker to isolate the defective generator is not sufficient to prevent further damage, since the defective generator will continue to supply power to a stator winding fault until its field excitation has been suppressed. Finally, the relays must certainly not trip undesirably during the running up of a generator.

The numerical algorithm of the generator differential protection is in principle simpler than that of the power transformer differential protection. No phase shifts, and no transformation ratios, typical of power transformers, must be numerically allowed for. In the case of generator differential protection, all the current transformers used to supply the information on the primary input and output currents could in theory have exactly the same characteristics, due to the same voltage and current level on both sides of the generator. This should further increase the chances for generator differential protection. Unfortunately, neither are the current transformers identical, nor have they equal secondary burden, if not for other reason then due to unequal length of secondary leads. This results in false differential currents which is particularly troublesome for external faults. The problem is further aggravated by the very long DC time constant of generators, T_G, which can be for generators in unit connection up to 600 ms [1]. The problem is still more pronounced for shunt reactors which have DC time constants of up to 1 second or even more.

Even though the differential relays are considered quite reliable and robust, there are situations when they may malfunction. Contradictory requirements of high sensitivity and selectivity are difficult to reconcile in cases of external faults (or external disturbances such as sudden loading) with small through currents which have very long decay times of the DC components of currents. One such problematic case is investigated later in the paper. A 400 kV shunt reactor had previously been sporadically disconnected by the differential protection after energization, sometimes after such a long time as 1 or 2 seconds.

2. DIFFERENTIAL PROTECTION

2.1 Basic principles

The generator differential protection function uses two mutually independent limits, to which magnitudes of the three fundamental frequency differential currents are compared at each execution of the differential protection function. The function is executed with 1 kHz rate. These two limits divide, independently of each other, the operate – block plane into two regions: the operate (trip) region and the block (restrain) region, see Figure 1. Two levels of protection are thus obtained:

1. The non-stabilized ("instantaneous", "high-set") differential protection, which is used for very high differential currents, where it should be beyond any doubt, that the fault is internal. This limit, (determined by the setting UnrestrainedLimit), is a constant, not proportional to the bias (restrain) current. No harmonic or any other restrain criterion is applied to this limit, which is therefore also called the unrestrained limit. The reset ratio of the characteristic is equal to 0.95.

2. The traditional stabilized, "percentage", differential protection applies a differential (operate) current, and the common bias (restrain) current, on the operate – block characteristic as shown in Figure 1. Here, the actual limit, where the protection operates, is adaptive, as the sensitivity of the protection is a function of the bias current. The protection is "stabilized" by the bias current. The fundamental frequency component of the highest generator current measured is taken as the bias. The operate – block characteristic is represented by a double-slope, double-breakpoint characteristic. The reset ratio is in all parts of the characteristic equal to 0.95.

The operate – block characteristic is tailor-made, in other words, it can be constructed by the user. A default operate – block characteristic is suggested which should give acceptably good results in a majority of applications. The operate – block characteristic has in principle three sections with a section-wise proportionality of the operate value to the common restrain (bias) current. The operate – block characteristic should be constructed so that in a certain protection application, it can be expected that for internal faults, the operate (differential) currents are always safely, i.e. with a good margin, above the operate – block characteristic. At the same time the characteristic must be such that for external faults, the false (spurious) operate currents are safely, i.e. with a good margin, below the operate – block characteristic.

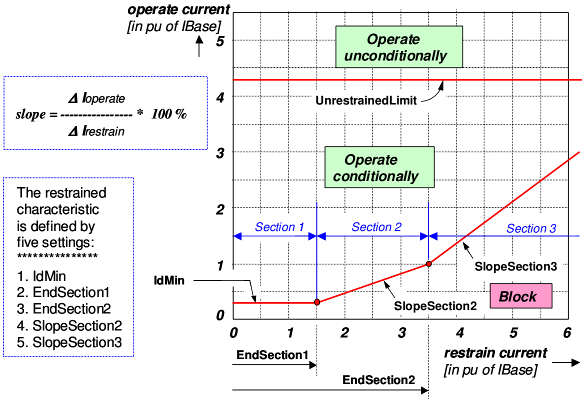

Figure 1. Characteristics of the generator differential protection. The base current will normally be the protected generator rated current.

To relieve the user somewhat from the burden of constructing an optimal operate – block characteristic, two special features supplement the basic stabilized differential protection function, making the generator differential protection a very reliable one.

2.2 Supplementary criteria

The two supplementary criteria have the power to either:

- enhance the protection (i.e. make it faster), or
- block the protection (withdraw, suppress trip)

The supplementary criteria are:

1. Internal / external fault discriminator.
2. Harmonic restrain.

The algorithm of the internal / external fault discriminator is based on the theory of symmetrical components. As far back as in 1933, Wagner and Evans [2], stated that:

1. The source of the negative-sequence currents is at the point of fault.
2. The negative-sequence currents distribute through the negative-sequence network.
3. The negative-sequence currents obey the first Kirchhoff's law.

The internal / external fault discriminator is a very reliable supplementary criterion. It securely discriminates with a high speed between internal and external faults. Typical response time of the discriminator is 8 – 10 ms.

- If a fault is classified as internal, then any eventual block signals by the harmonic criterion are overridden, and the differential protection operates very quickly without any further delay. Typical response time: 16 - 30 ms.

- If a fault (disturbance) is classified as external, then generally, but not unconditionally, a trip command is prevented. If a start signal has been set and the fault is classified as external, then the best sensitivity is temporaily decreased to 2 times IdMin, and the so called "cross-block" logic is applied. The "cross-block" logic requires that all the differential currents which caused their respective start signals to be set, are free of harmonic pollution. With other words, a trip command will only be issued if no harmonic block has been issued. If these requirements are fulfilled, then a minor internal fault, simultaneous with a predominant external fault, can be suspected. This conclusion can be drawn because at external faults, major false differential currents can only exist when one or more current transformers saturate. In this case, the false instantaneous differential currents are rich in higher harmonic components, the 2nd, the 3rd, the 5th, etc.

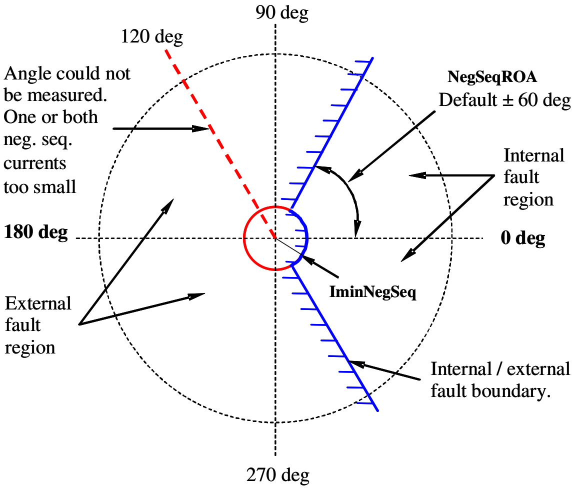

Figure 2. The characteristic of the internal – external fault discriminator. It is determined by two settings: IminNegSeq and NegSeqROA.

Figure 3 shows the trajectory of the phasor representing the negative sequence differential current in the polar plane for a fault on the stator winding. The deviation of the angle from the expected 0 degrees is due to transient current transformer saturation. The negative sequence phasor remains within the internal fault region at all times. The fault is definitely internal.

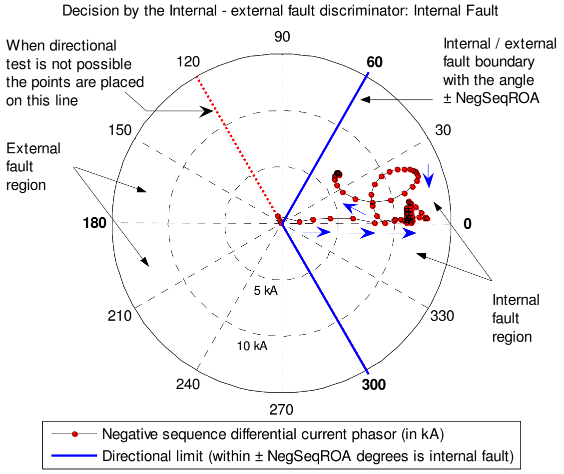

Figure 3. Trajectory of the phasor representing the negative sequence differential current in the polar plane. The phasor remains at all times within the internal fault region. The fault is definitely internal.

2.3 Enhanced stability with DC bias

Problems experienced by many differential protections are often due to the very long DC constants in the fault currents. These DC components are particularly unpleasant at external faults, where the persistent DC currents - even at otherwise rather moderate through currents - tend to saturate one or more current transformers. This is the cause of many inadvertent disconnections of generators for external faults. Similar problems arise when one tries to energize a shunt reactor. One such very typical example is investigated later in this paper.

To counteract these unpleasant phenomena, the sensitivity of the differential protection can be optionally temporarily decreased based on the DC offsets as measured in the three instantaneous differential currents.

Note that this DC desensitization is not active, if a disturbance has been detected and characterized as internal fault by the internal - external fault discriminator. No sensitivity or speed is lost for internal faults.

The above principle of the so called DC bias is in short as follows. The DC components are continuously extracted from the three instantaneous differential currents. The highest DC component of all three is then taken as a kind of a DC bias in the sense that the highest effective, temporary sensitivity of the protection (normally this is the sensitivity in Section 1 of the operate – block characteristic) is temporarily decreased as a function of this highest DC offset. The calculated DC bias current is not allowed to decay (from its highest ever measured value) faster than with a time constant T = 1 s. The value of the temporary effective sensitivity limit is limited upwards to the generator rated current, or 3.3 times that of IdMin, whichever is smaller. Consequently, similar to the DC bias current, the temporary extra limit decays exponentially from its maximum value with a time constant equal to T = 1 s. The temporary sensitivity is less than, or equal to the sensitivity in section 1 of the operate – bias characteristic, IdMin.

The DC bias feature should be used in case of shunt reactors and generators, where very long time constants can be expected. This temporary sensitivity limit is superior to the operate – block characteristic as has been set by the user, as long as it is above the latter. The feature is thus effective at moderate through currents, and ineffective at higher through currents.

Figure 4 shows by way of example how the DC offsets are on line extracted from the instantaneous differential currents. Observe that the decay of the calculated DC offset, which serves to determine the temporary sensitivity, is limited to exponential decay with T = 1 second. (Figure 4 belongs actually to the 400 kV shunt reactor example investigated later in this paper.) See also Figure 8.

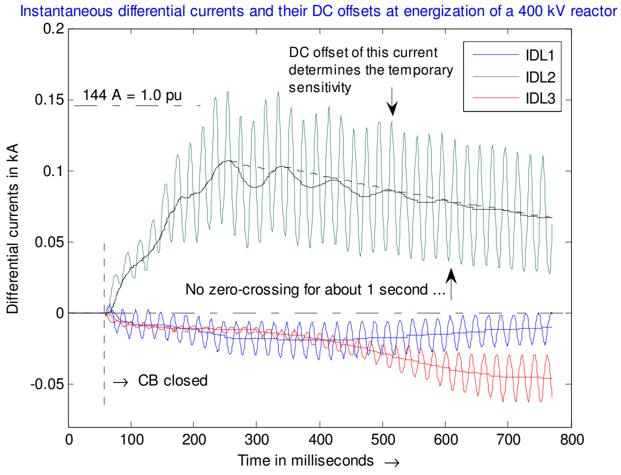

Figure 4. Shows how the DC offsets are on line extracted from the instantaneous differential currents from shunt reactor example later in this paper. Observe that the decay of the calculated DC offset, which serves to determine the temporary sensitivity, is limited to exponential decay with T = 1 second. See as well Figure 5 and Figure 8.

3. ENERGIZING A SHUNT REACTOR

3.1 Inrush currents to a reactor

The switching of a reactor gives rise to inrush current – a transient phenomenon related to saturation in the magnetic circuit. In principle, it is the same story as inrush current to a power transformer, but there are differences. A reactor keeps no remanence due to the air gaps. The inrush currents are thus generally lower than with power transformers. The highest are inrush currents in a phase where the instantaneous phase voltage is zero at the time when the contact is established. With no saturation of the iron core, this phase experiences the highest DC component, the current in this phase will reach the peak value which is approximately 2 * √2 = 2.82 times the value of the steady-state, normal current. As the peak flux – which started at zero – reaches after the first half-cycle twice the normal value and this flux most often means a degree of saturation of the iron core, the current will increase faster than flux after the saturation level flux has been reached and passed.

If no saturation, the first peak of the current with full offset would be 2.82 times the value of the steady-state, normal current. The actual peak currents rise to 3 – 5.5 times the value of the steady-state, normal current, higher values valid for smaller reactors, see [3].

Commonly, the linearity is guaranteed up to 120 % of the rated voltage. Specific requirements on linearity above 120 % -130 % of rated voltage lead to over-dimensioning and end up in extra cost …

During the first few cycles, the damping of the inrush current is fairly pronounced when the core steel goes into saturation giving rise to high current peaks. Later on, when the linear part of the flux – current relation has been reached the damping will be lower as the losses in the reactor get low. The time to fully balanced operation around zero flux in the core may be fairly long.

3.2 Inrush currents and differential protection

There are substantial differences between the differential protection of power transformers and shunt reactors with respect to inrush currents. In theory, things should be much easier for reactor differential protection …

With power transformers, the inrush currents flow exclusively into the winding which has first been switched onto the power system. Because the inrush current flows only on one side of the power transformer the whole of inrush current is directly reflected as the differential current. Most often, the very high contents of the 2^{nd} harmonic component in these false differential currents successfully prevent an unwanted trip.

With shunt reactors, exactly the same primary current flows on both ends of a phase winding of the protected reactor, where the currents are measured. With ideal, or at least absolutely identical current transformers, both with regard to their construction as well as with regard to their operating point (remanence and load in the secondary circuit), there would be no differential current at all – this goes without question! It is clear that for an inrush into a healthy shunt reactor all the differential currents that may arise are false, spurious, differential currents due to the differences in current transformers placed on opposite sides of the protected reactor. The waveforms of differential currents for inrush will therefore be very much different in case of shunt reactors in comparison to those with power transformers. The example investigated below is a proof of this.

3.3 The Shunt Reactor Problem

The relatively small, but persistent DC currents in primary currents can sooner or later drive the current transformers into saturation. If the current transformer on the other side of the reactor does not saturate at exactly the same instant, and to the same degree, the false differential currents may be high enough to cause an unwanted disconnection, [4, 5].

The problem is that the fundamental frequency currents which flow into the reactor after its connection to the voltage source are not much above the normal load currents. The differential protection is thus “waiting” for any differential currents at its best (highest) sensitivity in section 1 of the operate – bias characteristic. The danger of an unwanted operation is imminent!

The real life example which follows shows the connection (i.e. normal loading) of a 400 kV shunt reactor to the power system. Previously, when protected with another differential protection, the reactor was often disconnected inadvertently after having been switched to the power system.

4. SHUNT REACTOR EXAMPLE

It is known that one of the principle difficulties with shunt reactors is inadvertent operations of differential protection during energizing of the reactor. While the power transformer differential protection normally mal-operates within 100 ms (if special, dedicated restraints, such as the harmonic or waveform restrain, are not effective), the differential protection of a reactor may mal-operate 500 ms, or even 1 to 2 seconds after circuit breaker has been closed.

Figure 5 shows the currents recorded during energization of a 400 kV shunt reactor. The recorded currents are not the true currents, but currents as seen by the differential protection, i.e. the secondary currents of the current transformers, but referred back to primary side.

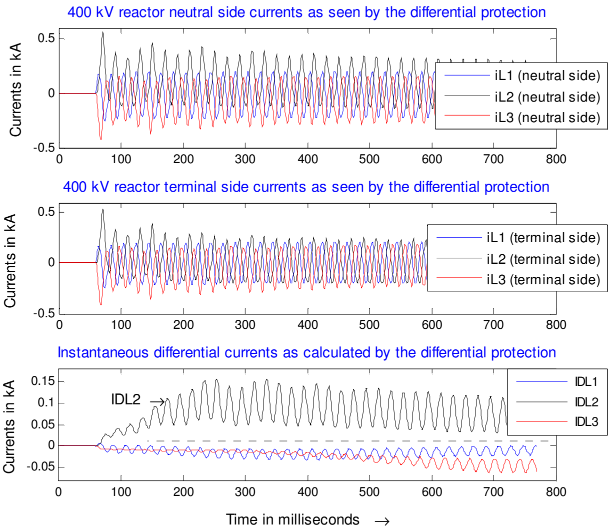

Figure 5. The reactor currents as measured, and the calculated instantaneous differential currents. The instantaneous differential currents are totally false, spurious, and exist only due to differences between the current transformers.

Observe the very interesting instantaneous differential currents. They have all a pronounced DC offset, in particular differential current in phase L 2. **I**nvestigation of the harmonic distorsion of these false instantaneous differential currents showed that there was very little 2^{nd} harmonic component: the maximum amount of the 2^{nd} harmonic was found to be 15 %, typically there was between 0 % and 10 %. Consequently no help could be expected from the harmonic block feature traditionally used against inadvertent trip under inrush conditions. Tests have proved that not even the lowest possible harmonic limit, which is 5 %, could prevent an inadvertent disconnection of the reactor, with any good sensitivity of the differential protection.

Figure 6 shows the trajectory of false fundamental frequency differential current of L 2 phase in the operate – block current plane. The differential current enters the OPERATE region as determined by the operate – block characteristic of the differential protection 110 ms after the circuit breaker has been closed. If it were not for the so called DC bias feature, which temporarily desensitized the differential relay, an unwanted trip command would have been issued. If the DC bias feature is activated, then, a temporary sensitivity limit is applied, which is above than the operate – block characteristic, as constructed and set by the user. This temporary limit is in Figure 6 designated as “Dynamic” operate – bias characteristic. Figure 7 shows these limits and the differential current against time! This figure is easier to understand than Figure 6.

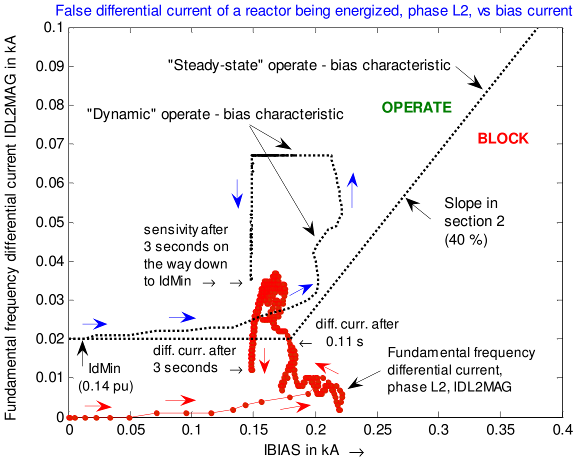

Figure 6. The false fundamental frequency differential current of L 2 phase in the operate – block current plane. Observe that the differential current enters the OPERATE region 110 ms after the circuit breaker has closed. The differential current leaves the OPERATE region 1.5 s later. As harmonic block is not efficient, an unwanted trip command could be expected. However this is prevented by the so called DC bias, which temporarily decreases the sensitivity as shown.

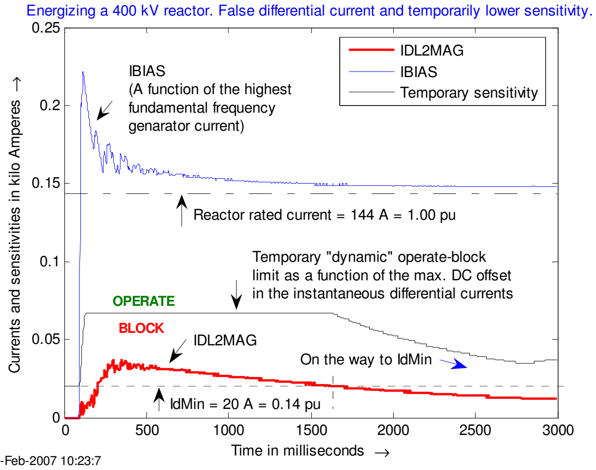

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Figure 7. The differential, as well as the bias currents and the actual sensitivities shown as functions of the time. Observe that the fundamental frequency differential current IDL2MAG is below the “dynamic” limit at all times. Any un-wanted trip is thus impossible.

Finally, Figure 8 shows that the DC offset in the spurious, false instantaneous differential currents can change sign. This has nothing to do with the real primary currents, but so much more with the reality of the current transformers. Changing the sign of the DC offset is a consequence of the different dynamic behaviour of the current transformers on opposite sides of the reactor phase L 2 winding. Also for this reason, a special artificial exponential curve is constructed within the differential protection, with a decay constant of T = 1s, which then determines the temporary sensitivity of the protection.

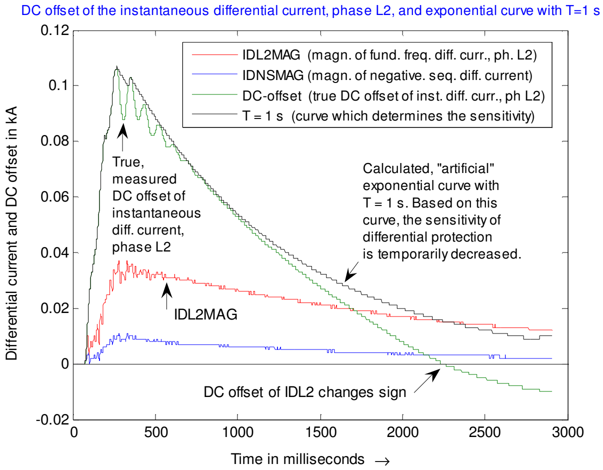

Figure 8. The DC offset in the spurious, false instantaneous differential currents can change its sign. Changing the sign of the DC offset is a consequence of the different dynamic behaviour of the current transformers on opposite sides of the reactor winding. For this reason, a special artificial exponential curve is calculated, wich can decay not faster than with a time constant of T = 1s. See also Figure 4 and Figure 7!

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