TRANSFORMER DIFFERENTIAL PROTECTION IMPROVED BY IMPLEMENTATION OF NEGATIVE-SEQUENCE CURRENTS

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Abstract. Existence of a relatively high negative-sequence current is in itself a proof of a disturbance on the power system, possibly a fault. The paper describes the usage of the negative-sequence currents in order to both detect and positively determine the position of the fault with respect to the protected zone, and thus avoid some typical weaknesses of the power transformer differential protection. Some examples of these are long delays for heavy internal faults, unwanted operations for external faults, and insensitivity to low-level turn-to-turn faults, which can be left to develop into high-level faults – with more severe damage to the power transformer – before they can be detected.

Keywords. Relay protection, power transformer, sensitive differential protection, negative-sequence currents, internal-external fault discriminator.

I. INTRODUCTION

Two of the most typical weaknesses of the power transformer differential protection are long delays or even a failure to operate in case of heavy internal faults with current transformer saturation, and unwanted operations for external faults. A CIGRE survey for the period 1995-1996 [1] states that the differential protection fails to operate for internal faults or operates for external faults in 3 % of cases.

Long delays for heavy internal faults – they can be of the order of several tens or even hundreds of milliseconds – are a consequence of the harmonic distortion of the fault currents as they are seen by the differential relay. The harmonic distortion is due to initial heavy saturation of the current transformers under fault conditions. The harmonic restrain can delay / prevent immediate operation of the restrained (percentage) differential protection.

Further, power transformer differential protections show a tendency for unwanted operations for faults external to the protected zone with the power transformer – particularly for external earth faults.

These disadvantages can be avoided if the position of the fault (internal or external with respect to the protected zone) is quickly and correctly determined. An internal - external fault discriminator, based on the negative-sequence differential current, or more precise, on the separate contributions to the total negative-sequence differential current from both (all) power transformer sides, can do the job.

The internal-external fault discriminator determines the position of the fictitious source of the negative-sequence currents with respect to the zone protected by the differential protection. If the source of the negative-sequence currents is found to be inside the zone, then the fault is internal. If the source is found to be outside the zone, the fault is external.

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 fictitious 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, based on the above principles, has shown itself to be very fast and reliable. Thus, when a fault is positively characterized as internal, all eventual block (restrain) signals, such as for example the harmonic block signals, or the waveform block signals, can be ignored, and the differential protection can operate very quickly. Operate times of a little more than ½ of the period, where otherwise operate times of at least one period or – as a worst case - several periods could be expected, are not unusual. Other advantages besides those mentioned above are obtained, such as better sensitivity of the protection.

However, the internal-external fault discriminator only works when the protected transformer is not just energized, but is as well connected to load.

Both detection of faults, and a secure discrimination between internal and external faults can be achieved based on an analysis of the negative-sequence differential current, or more exact, based on an comparative analysis of its two (or three at three-winding transformers) separate contributions to the total negative-sequence differential current. Supplemented with the fault discriminator, the power transformer differential protection:

- operates promptly for heavy internal faults,
- detects low-level internal faults, as inter-turn,
- is stable against external faults.

II. PRINCIPLE OF THE DISCRIMINATOR

- **Default connection of current transformers**

In order to avoid misunderstandings about what is meant by “the same direction”, and what by the “opposite direction”, an explanation is in its place.

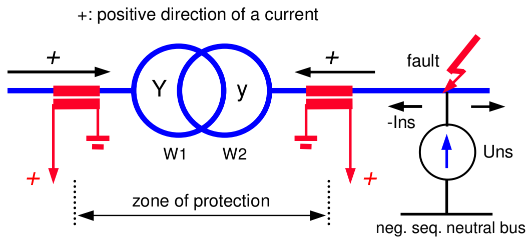

Figure 1. The commonly used (default) connection of current transformers, and the definition of the positive direction of a current. Transformer Yy0.

For an external fault (with the fictitious negative-sequence source at the point of fault) the negative-sequence currents enter the healthy power transformer on one side, and leave it on the other side, properly transformed. According to Figure 1, the negative-sequence currents on the respective sides of the (Yy0) power transformer are of the opposite directions; or more precisely, the differential protection sees the currents as opposite, with a relative phase shift of 180˚ between them.

For an internal fault (with the fictitious negative-sequence source at the point of fault) the negative-sequence currents leave the faulty transformer on both sides. According to Figure 1, the currents on the respective sides of the (Yy0) power transformer have the same direction; the differential protection sees these currents with a relative phase angle of 0˚. In reality, the relative phase angle between these currents may differ somewhat from 0˚, due to possible different negative-sequence impedance angles of the electrical circuits to the left, and to the right, from the internal fault. Further, the magnitudes of the negative-sequence currents depend on the magnitudes of the negative-sequence impedances of circuits on the respective sides.

In general, to be able to talk about 180˚, or 0˚, any phase shift introduced by the transformer, e.g. 30˚ of an Yd1 transformer, must be compensated.

- **Negative-sequence differential current**

The same coefficient matrices can be used for the calculation of the purely negative-sequence differential currents as for the calculation of the “usual” differential currents (containing generally all symmetrical components) only that in order to get the negative-sequence differential currents purely negative-sequence currents must be fed. The matrix coefficients allow for both power transformer phase shift (e.g. 30˚) and transformer ratio (e.g. 2:1). The coefficients are such that the magnitudes of all currents are referred to the power transformer HV side (primary, winding 1) in order to form a common basis for the comparison of the negative-sequence currents from both (all) power transformer sides. The coefficients can as well remove the zero-sequence currents, where required, but this is of no consequence in this respect. Because the negative-sequence differential currents are symmetrical, only one differential current needs to be calculated, for example the negative-sequence differential current in phase L1, i.e. Idns_L1. The real and imaginary parts are calculated separately. The negative-sequence differential current must be calculated on a regular basis, e.g. at a rate of 1 kHz.

$$\begin{bmatrix} Idns\_L1 \\ Idns\_L2 \\ Idns\_L3 \end{bmatrix} = \underbrace{\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} * \begin{bmatrix} Ins\_A \\ Ins\_B \\ Ins\_C \end{bmatrix}}_{\substack{\text{Contribution to total} \\ \text{negative seq. current} \\ \text{from HV side (e.g. Y)}}} + \underbrace{\begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} * \begin{bmatrix} Ins\_a \\ Ins\_b \\ Ins\_c \end{bmatrix}}_{\substack{\text{Contribution to total} \\ \text{negative seq. current} \\ \text{from LV side (e.g. d)}}}$$

The total negative-sequence differential current Idns_L1 is very low (theoretically zero) in case of an external fault, and high (theoretically higher than zero) in case of an internal fault. More important, however, than the total negative-sequence differential current itself, are in this context the two (or three for a three-winding power transformer) contributions to the total negative-sequence differential current: the one from the HV (W1) side, and the other from the LV (W2) side. These two contributions are compared as to their directions by the fault discriminator, in order to find out whether the fault is internal or external.

- **Internal - external fault discriminator**

The two contributions to the total negative-sequence differential current are expressed as phasors, each with its magnitude and phase position in the complex plane, as, for example, in Figure 2. For a trustworthy directional comparison of the two phasors, magnitude of each of them must be above a certain minimum value otherwise no comparison is allowed. This threshold which is a setting must be set well above the small values of the negative-sequence currents that can be measured during normal operation of the power system. A practical value is 2 % of transformer rated current, or higher.

If both contributions to the total negative-sequence differential current exceed the threshold, (which in itself is as a sign that a disturbance must have happened, as the negative-sequence currents are a superimposed, a pure-fault quantity), the directional comparison is carried out. The relative phase angle between the phasors is determined. Based on the value of this relative phase angle, an internal or an external fault is declared. See Figure 3.

Figure 2 illustrates the situation for an external single-phase earth fault on the earthed Y side of an Yd1 transformer. There was no appreciable current transformer saturation. Observe that at any point of time, the angle between the two contributions was 180˚. The geometric sum of the two contributions, which is equal to the negative-sequence differential current, was practically zero at all times, which corresponds to the fact that the fault was external.

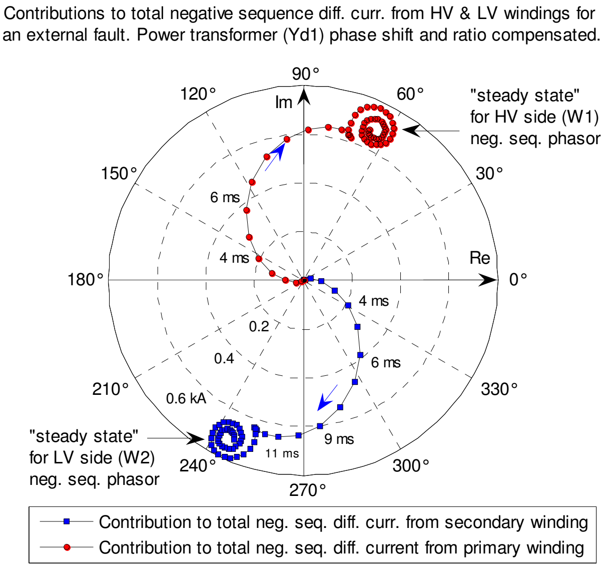

Figure 2. Trajectories of the phasors representing the contributions to the negative-sequence differential current from the Yd1 power transformer HV and LV sides, for an external earth fault on the HV side. The Yd1 transformer phase shift and ratio compensated. No current transformer saturation.

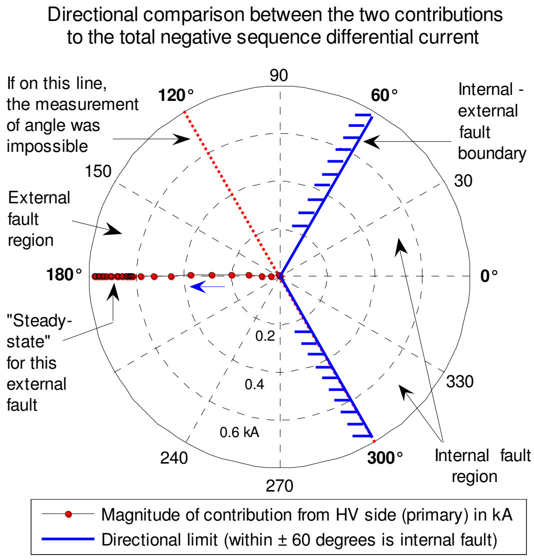

Figure 3. Trajectory of a phasor with a magnitude equal to the magnitude of the contribution from the HV (W1) side of the power transformer, and a phase angle equal to the relative phase angle between both contributions. The angle is 180˚ → the fault was definitely external. Observe the internal - external fault boundary.

Figure 3 shows a polar plot where the relative phase angle between the two phasors from Figure 2 is displayed, which was near 180˚ practically all the time. There could be no doubts that the fault was external. Note the internal - external fault boundary, here determined with ± 60˚. An internal fault would be declared if the relative angle initially stayed within ± 60˚ under at least a short interval of time.

The internal - external fault boundary, determined by the so called Relay Operate Angle ± 60˚, as in Figure 3, has been found optimal. It was verified by more than 250 tests with simulated faults. The Relay Operate Angle is a setting with a range from ± 30˚ to ± 120˚. The default (i.e. the recommended) value is ± 60˚, which favours somewhat security in comparison to dependability. (Security is a measure of the relaying equipment not to trip incorrectly. Dependability is a measure of the relaying equipment's ability to correctly clear a fault.)

The directional test is very fast: the first indication about the position of the fault is obtained typically in 2 to 3 milliseconds. In order to cope with any possible transients the directional test must have some short intentional delay. Any decision on the character of a fault (internal – external) must be confirmed several times in succession to be accepted ("security count"). The overall response time is inversely proportional to the magnitudes of the fault currents. The very trustworthy information on whether a fault is internal or external is obtained typically in 6 to 8 milliseconds after the fault.

If any of the two negative-sequence currents is too small, no decision is taken regarding the relative position of the fault, and the feature remains inactive rather than to produce a wrong decision. The relative angle is in such cases assigned the value of 120˚, (2.09439 radians), see Figure 3.

The internal - external fault discriminator only works if the protected power transformer is connected to a load, so that currents can flow on both sides of the power transformer, or at least two sides in case of a three-winding power transformer. The good side of this is for example, that the initial magnetizing current inrush is not recognized as an internal fault which would result in unwanted trips.

- **Current transformer saturation**

One of the most important factors which must be considered when setting the directional boundary (i.e. the Relay Operate Angle) is the current transformer saturation. The case documented in Figure 2 and Figure 3 was a rather favourable one, with negligible current transformer saturation.

Current transformer saturation may cause the measured phase angle to differ from 180˚ for external faults, and from 0˚ for internal faults. If the differential protection is fed by the secondary current of a saturated current transformer, the magnitude of the fundamental harmonic component of the true power system current is apparently decreased, while the phase position is apparently shifted in the positive direction (i.e. counter-clockwise) by up to 45˚, or even more in cases of more extreme saturation. This fact alone should limit the Relay Operate Angle to at least ± 45˚. Figure 4 and Figure 5 illustrate conditions for an external, and an internal fault, respectively, with transient current transformer saturation. In Figure 5, due to current transformer saturation, the trajectory leaved temporarily the internal fault region, but by that time, the trip command had already been given. Neither could only three points in the external fault region change the decision of the discriminator.

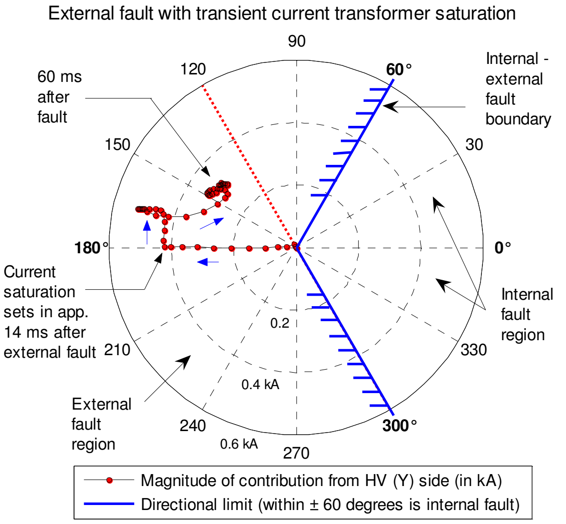

Figure 4. An external fault with appreciable current transformer saturation, the first 60 ms after fault.

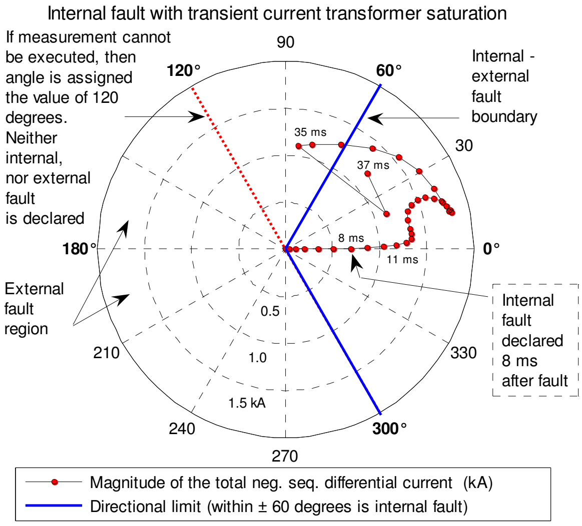

Figure 5. An internal fault with severe current transformer saturation; the first 37 ms after fault. Trajectory of a phasor with a magnitude equal to the magnitude of the total negative-sequence differential current, and a phase angle equal to the relative phase angle between both contributions to the total negative-sequence differential current.

Between 5 to 10 milliseconds to full current transformer saturation are sufficient to produce a correct discrimination between faults. Current transformers typically saturate in 20 milliseconds.

III. IMPROVEMENT OF THE PROTECTION

- **No extra delays at heavy internal faults**

As the fault discriminator proved to be very reliable, it has been given a high priority. If, for example, a fault has been detected, and the start signals have been set by the restrained differential protection, while the fault classified as internal, then any block signals, produced by either the harmonic or the wave-form restraints, are ignored. As a result, the operate times of the protection are below 20 milliseconds even at heavy internal faults with severely saturated current transformers, where otherwise delays of several tens or even hundreds of milliseconds could be expected.

- **Better sensitivity to low-level internal faults**

If, for some reason, for example because of uncompensated movements of an On-Load-Tap-Changer, the operate - restrain characteristic of the restrained differential protection must be set relatively high, then minor internal faults cannot be detected before they evolve into major ones, with higher unbalanced currents at the terminals of the protected transformer. A majority of transformer failures can be traced to internal winding insulation failure, usually turn-to-turn faults. If only a couple of turns are short-circuited, then the fault may not be felt by the restrained differential protection in spite of the very high fault currents within the short-circuited part of the winding. Such faults may be left to develop into more serious and costly-to-repair faults, often including transformer iron core.

A special new protection, based exclusively on the internal - external fault discriminator has been introduced, which is an independent part of the complete power transformer differential protection, [3]. This protection is called the Sensitive Negative-sequence Differential Protection. It has no logical connection with the restrained differential protection algorithm. No start signal must be issued by the restrained differential protection in order to activate the Sensitive Negative-Sequence Differential Protection. The latter starts independently whenever the magnitudes of both contributions to the total negative-sequence differential current are higher then the minimum threshold, as discussed in the paragraph ‘Internal - external fault discriminator’. This threshold can be set as low as 2 % of the power transformer rated current. If a low-level fault has been detected in this way, and found to be internal, a trip command is issued after a short intentional delay, added as an extra precaution. Inter-turn faults including more than about 1 % of turns of a winding can be detected. Operate times in the range of 30 ms to 40 ms can be expected, which can be compared to the electro-mechanical Buchholtz- or sudden pressure relays with their operate times of 50 ms to 150 ms.

- **Stability against external faults**

External faults happen at least ten times more often than internal faults in power transformers. To avoid eventual stability problems following transformer disconnection for external faults, and the high cost of unwanted outages, security against external faults has become increasingly important. Consequently, if an external fault or disturbance has been detected, any trip request is cancelled.

There is, however, an exception to this rule, which copes with simultaneous lower-level internal faults, such as inter-turn faults, which may occur immediately after (and often due to) an external fault. The idea behind this feature is as follows.

If an external fault is being signalized by the fault discriminator, and one or more start signals have been set, but at the same time, no harmonic block signals exist, then a simultaneous low-level internal fault can be suspected. The faulty transformer can be disconnected immediately, without having to wait for the external fault to be cleared first by some other protection. As a special precaution measure against any unwanted trip, the so called “cross-blocking” logical scheme (an On / Off setting option otherwise) is imposed temporarily.

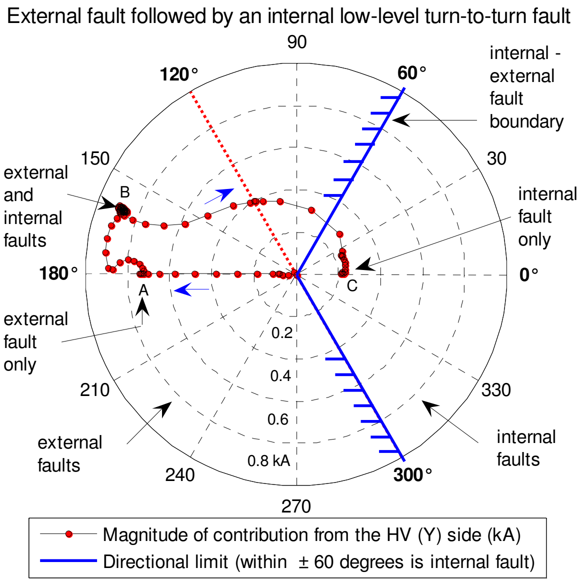

Figure 6. Trajectory of a phasor with a magnitude equal to the magnitude of the contribution to the total negative-sequence differential current from the HV (Y) side of an Yd1 power transformer, and a phase angle equal to the relative angle between both contributions. Observe that the trajectory remains in the external fault region for a dominant external fault and a simultaneous minor internal fault.

The above reasoning is valid if the zero-sequence currents have been eliminated from the differential currents where necessary (a majority of power transformers cannot transform the zero-sequence), and movements of an eventual On-Load-Tap-Changer compensated for. In that case, major false differential currents for an external fault can only appear if current transformers saturate. The instantaneous differential currents are in such cases heavily polluted with higher harmonic components.

Figure 6 shows how the internal – external fault discriminator sees a case where a dominant, heavier external fault occurred first, followed by a low-level (internal) turn-to-turn fault. The external fault was a single-phase earth fault (L1-E) on the earthed Y side of an Yd1 transformer (at t = 42 ms), while the internal fault was an inter-turn fault (10 %) in phase L2 on the HV-side Y winding (at t = 62 ms).

Point A in Figure 6 corresponds to the external fault only. Point B corresponds to simultaneous external and internal faults. Point C corresponds to the situation where the external fault would be cleared by some other protection, while the internal fault persisted. In a real application, the restrained differential protection would operate already at point B and disconnect the faulty transformer, in spite of the fact that the point B lied deep in the block region because of the dominant external fault. The faulty power transformer would be disconnected 20 ms (exclusive the output relay) after the inception of the internal fault in spite of the fact that an external fault was being signalized.

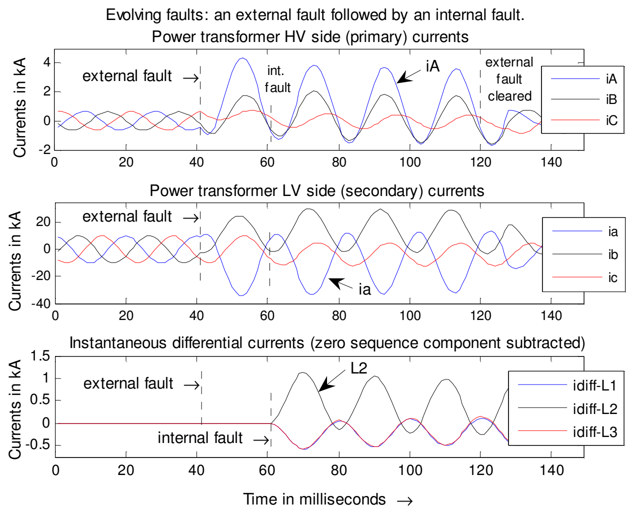

Figure 7. An external single-phase earth-fault (L1-E) on the HV (Y) side of an Yd1 power transformer at t = 42 ms, followed by an internal turn-to-turn fault (10 %) in phase L2 on the HV side winding at t = 62 ms. External fault was cleared at t = 128 ms.

Figure 7 displays some of the currents for the above example case corresponding to what was shown in Figure 6. Observe that the instantaneous differential currents were zero until the internal turn-to-turn fault occurred. The zero-sequence currents were subtracted as they could not pass through the Yd1 power transformer. Observe that the instantaneous differential currents are clear of harmonic pollution.

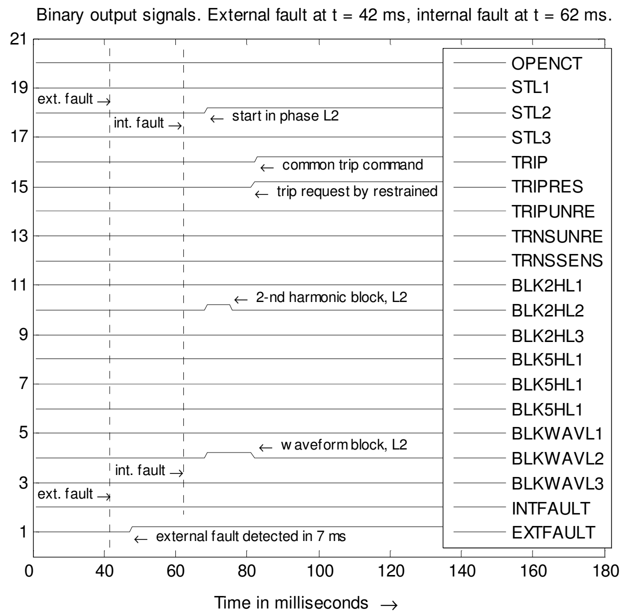

Figure 8. Binary output signals of the complete differential protection. The faulty transformer was tripped 20 ms after the internal fault. It was tripped by the restrained differential protection in spite of the fact that an external fault was being signalized.

IV. SYMMETRICAL FAULTS

The negative-sequence-current-based directional principle offers a fast and reliable discrimination between external and internal faults. This is easy to understand in case of unsymmetrical faults where the negative-sequence system is expected to exist just as long as the fault. But the principle is as well efficient in case of balanced, symmetrical faults. The reason is that when a symmetrical three-phase fault occurs, a fictitious negative-sequence current source exists for a while at the fault. It exists until the Direct Current components in the fault currents die out [4]. This interval of time is usually long enough for the fault discriminator to do its job. The rationale behind this is as follows. In the case of three-phase faults, fault currents in at least two phases experience a transient DC offset, which is of opposite direction in both phases. A frequency analysis of the maximum possible DC offset, decaying with a time constant Tdc = 50 ms, shows that its contents of the fundamental harmonic, i.e. 50 Hz, is 10.46 % in the first period following the fault inception. These extra 10.46 % of fundamental harmonic currents can be thought of as added (with the opposite sign / phase angle) to the fundamental frequency fault currents in the two phases. The balanced three-phase fault is thus initially felt as unsymmetrical and the position of the fault can be correctly determined. See APPENDIX.

V. CONCLUSIONS

The existence of relatively high negative-sequence currents is per se an indication of a disturbance, possibly a fault, as the negative-sequence currents are superimposed, pure-fault quantities. The negative-sequence quantities are particularly suitable for different kinds of directional tests. One of the advantages of the negative-sequence system, when compared to the zero-sequence system, is that the negative-sequence system is not stopped at power transformers of the Yd, or Dy connection. Further, the usage of the negative-sequence system is not limited to faults including earth. Moreover, even balanced, symmetrical faults can be successfully treated due to the transient three-phase fault generated negative-sequence current.

The negative-sequence quantities are extensively used in the field of relay protection, particularly in the protection of power lines. The negative-sequence currents can as well be applied with advantage to the protection of power transformers. However, the task of determining the position of a fault as inside or outside the protected zone which includes a power transformer is complicated by the changes in magnitudes and the phase shifts associated with power transformers. But, if these are properly compensated, the negative-sequence currents are a good means to determine the position of a fault with respect to the protected zone.

The internal - external fault discriminator, based on the directional comparison carried out on pairs of contributions to the total negative-sequence differential current, proved very reliable. It takes typically only a couple of milliseconds to detect a fault, and altogether 6 to 8 milliseconds to characterize it as internal or external. By using the discriminator as a complement to the traditional restrained differential protection, some of its typical weaknesses, namely extra delays in case of heavy internal faults with current transformer saturation, and the danger of unwanted operations for external faults, is diminished. Sensitivity of the protection to low-level faults, such as inter-turn, is increased.

VI. REFERENCES

[1] CIGRE. Study Committee 34. Working Group 01. Final Report: “Reliable Fault Clearance and Back-up Protection.” Sweden, 1997.

[2] Wagner, C.F. and Evans, R.D.: “Symmetrical Components", McGraw-Hill, New York & London, 1933.

[3] Zoran Gajic, Ivo Brncic, Birger Hillström: “Sensitive Turn-to-turn Fault Protection for Power Transformers.” Western Protective Relay Conference, Spokane, Washington, USA, 2005

[4] Jonas Johansson: “Fast Estimation of Symmetrical Components.” Master Thesis, Department of Industrial Electrical Engineering , Lund University, Sweden, 2002.

VII. APPENDIX

A simulation of a balanced, symmetrical three-phase internal fault in an Yd1d5 three-winding power transformer should shed some light on the issue “internal – external fault discriminator and symmetrical faults”. Thanks to the transient existence of the negative-sequence system, faults can be distinguished as internal or external, even for balanced, symmetrical three-phase faults.

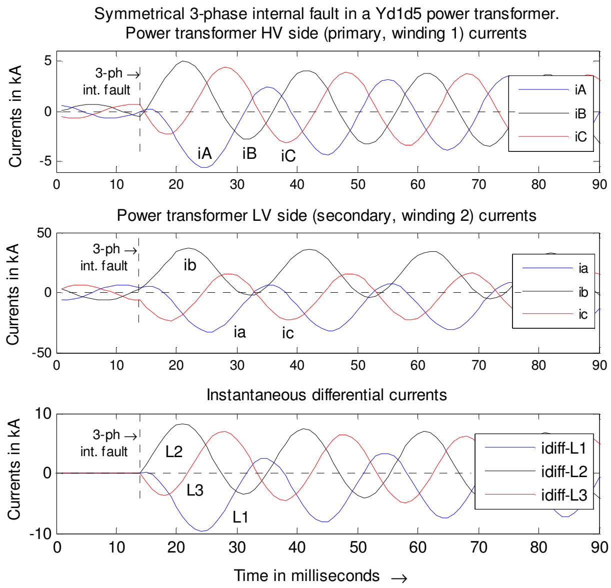

Figure 9. Instantaneous currents for an internal symmetrical three-phase fault on the Y side of an Yd1d5 power transformer. Currents flowing on the tertiary side are not shown. No current transformer saturation in this case. Observe the high DC offsets.

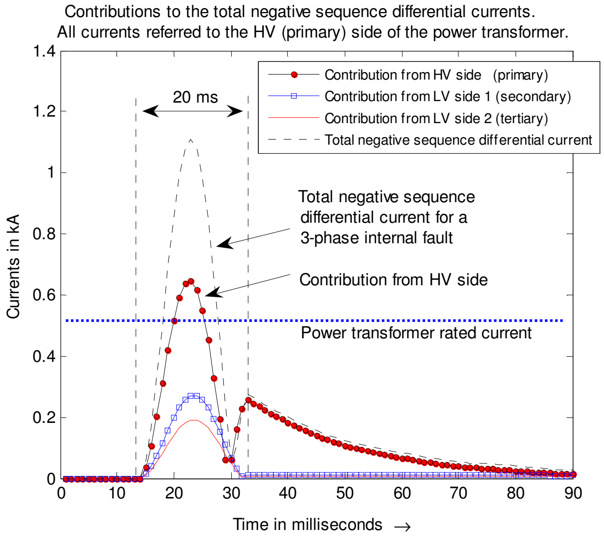

Figure 10. The total negative-sequence differential current, and the three contributions to it from the three power transformer sides. Observe that the transient negative-sequence currents are rather high. Two intervals of time characterize this transient phenomenon: the 1st 20 ms after the fault inception, and the time after that. Compare to Figure 12.

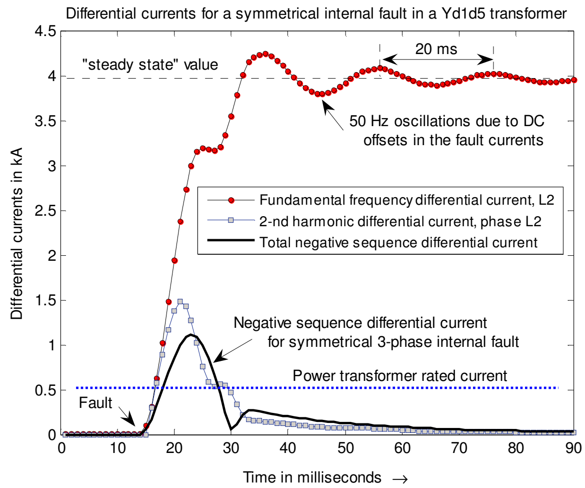

Figure 11. Magnitudes of some of the differential currents for a symmetrical internal fault. After the 1st period, the negative-sequence-, and the 2nd harmonic differential currents decay exponentially and simultaneously with the DC offset of the fault currents as they are seen by the protection relay.

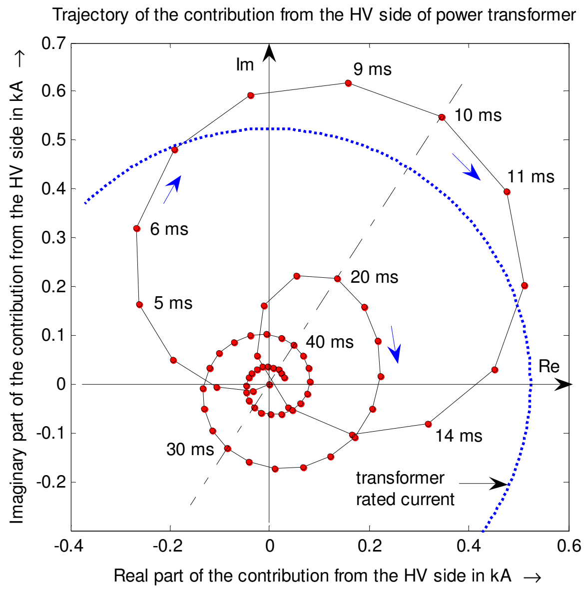

Figure 12. Trajectory of the contribution to the total negative-sequence current from the power transformer HV (W1) side. Compare to Figure 10! Note that the magnitude of the phasor reaches its maximum 10 ms after the fault. The spiral, from 20 ms, and on, corresponds to the exponential decrement of the magnitude of this negative-sequence current. Compare Figure 12 to Figure 2!

Frequency spectrum of the DC offset decaying with a time constant Tdc = 50ms is as follows:

1. 50 Hz → 10.50 %
2. 100 Hz → 5.24 %
3. 150 Hz → 3.50 %

The Fourier analysis was performed with Matlab function psbfft_scope.