Improved power transformer protection using numerical relays

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Large power transformers belong to a class of very expensive and vital components in electric power systems. If a power transformer experiences a fault, it is necessary to take the transformer out of service as soon as possible so that the damage is minimized. The costs associated with repairing a damaged transformer may be very high. The unplanned outage of a power transformer can also cost electric utilities millions of dollars. Consequently, it is of a great importance to minimize the frequency and duration of unwanted outages. Accordingly, high demands are imposed on power transformer protective relays. The requirements include dependability (no missing operations), security (no false trippings), and speed of operation (short fault clearing time).

The operating conditions of power transformers do not make, however, the relaying task easy. Protection of large power transformers is perhaps the most challenging problem in the power system relaying area.

Advanced digital signal processing techniques and recently introduced Artificial Intelligence (AI) approaches to power system protection provide the means to enhance the classical protection principles and facilitate faster, more secure and dependable protection for power transformers. Also it is anticipated that in the near future more measurements will be available to transformer relays owing to both substation integration and novel sensors installed on power transformers. All this will change the practice for power transformer protection. This paper briefly reviews the state of the art, but is primarily devoted to discussion of the new approaches and future directions in digital relaying for power transformers.

Problems in differential relaying for power transformers

The Figure 1 presents general hardware configuration of a digital power transformer relay. The differential relaying principle is used for protection of medium and large power transformers. This superior approach compares the currents at all the terminals of the protected transformer by computing and monitoring a differential (unbalance) current. The non-zero value of the differential signal indicates an internal fault. However, the transformer operating conditions may introduce problems as presented in Table I.

The operating criteria for transformer differential protection used to overcome the reported difficulties can be classified as:

- the principles broadly used in today's products,
- the advanced numerical principles already invented but not broadly implemented,

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- the AI approaches already suggested but not sufficiently investigated.

This classification is reflected in Figure 2.

The relaying methods applied in today's products basically use the current signals and limit the analysis to the fundamental frequency components and higher harmonics of those signals.

The advanced numerical principles use more information including voltage signals as well as signal features other than just harmonics.

The AI methods tend to utilize all the available information. As shown in the figure, the numerical complexity of an algorithm is the price to pay for processing more information.

Classical restraining criteria

The Figure 3 presents a simplified flow chart of the logic of a digital differential relay for power transformers. Within this frame, the second or higher harmonic are used to prevent false tripping during magnetizing inrush conditions; the fifth harmonic is commonly used to restrain the differential relay during stationary overexcitation conditions; while the biased percentage characteristic is used to prevent false tripping during external faults.

However, this traditional approach may not be able to deal with certain problems as revealed in Table I.

Advanced numerical restraining criteria

The new operating principles have been invented for digital relays. They result in more involved numerical operations rather then just in simple increase of number of functions known from the era of electromechanical relays and bring certain improvements in protective relaying for power transformers as shown in Table II. These principles can be classified between the global approaches and phenomena specific approaches as explained below.

Global approaches

By the global approach we mean a relaying algorithm that recognizes internal faults versus all the other phenomena in a power transformer without specifically classifying the later into magnetizing inrush, overexcitation and external faults.

<u>Model methods</u>

This family of approaches solves on-line a mathematical model of a fault-free transformer. Either certain parameters of the model are computed assuming the measured signals; or certain fraction of the terminal variables are computed based on all the remaining signals, and next compared to their measured counterparts. In the first case, the values of the calculated parameters differentiate internal faults from other disturbances. In the second case, the difference between the calculated and measured signals enables the relay to perform the classification. These approaches call for voltages and currents at all the terminals to be measured.

<u>Differential power method</u>

Another relaying principle uses the differential active power to discriminate between internal faults and other conditions. Instead of the differential currents, the differential power is computed and monitored. The operating signal is a difference between the instantaneous powers at all the transformer's terminals. This approach calls for measuring the voltages at all the terminals, but pays back by enabling avoiding the vector group (angular displacement between the current and voltages at different windings) and ratio compensation. The dependability of this method may be further enhanced by compensating for the internal active power losses — both in copper, and in iron.

In addition, having the active power available, the method enables one to compute the energy released in the tank and to emulate the back-up protection — both the accumulated and sudden pressure gas relays.

<u>Multi-setting overcurrent principle</u>

Severe internal faults may be recognized by the differential relay based only on the amplitude of the differential current without checking any extra conditions (unrestrained tripping). If the amplitude of the current is higher than the highest possible value under no-internal fault conditions (the inrush current, as a rule), then the relay trips without further analysis.

The Figure 4 presents amplitudes of the differential currents under the load, overexcitation, external fault, magnetizing inrush and internal fault conditions. The classical unrestrained differential overcurrent element must apply the threshold Δ set above the maximum non-internal fault current (Figure 4). If so, internal faults denoted as the class A are tripped by the overcurrent element while all other faults of the classes B to D must wait to be detected by the restrained element.

However, the internal faults of the class B may be distinguished from external fault and overexcitation phenomena by the overcurrent element working with the second lower threshold Δ_1 (Figure 4). If so, the internal faults of the category A are detected by the overcurrent principle with the threshold Δ. The internal faults of the category B are detected by the overcurrent element with the threshold Δ_1 if the inrush hypothesis is rejected by the other relaying principle such as the second harmonic restraint. The external fault and overexcitation conditions may not be checked at all since they are ruled-out be the overcurrent element (Δ_1). Similar reasoning applies to the faults of the categories C and D.

The principle of the multi-setting overcurrent element is implemented as shown in Figure 5 and represents a solution that can be placed between the traditional restrained and unrestrained differential functions. This approach enables reduction of the operating time particularly for the internal faults with medium levels of the fault current (the classes B and D in Figure 4). This approach enhances dependability by speeding-up the operation and covering the low-current internal faults.

Phenomena specific approaches

By the phenomenon specific approach we mean a relaying algorithm that restraints the relay from tripping only in one particular non-internal fault related situation (such as inrush) although some of the restraining algorithms occasionally deliver an extra blocking during other conditions as well.

Flux based inrush restraint

This relaying algorithm differentiates internal faults from the inrush and overexcitation conditions based on the calculated flux in the core. As its advantage, this approach tides together the cause of the problem (saturation of the core as a source of the current unbalance) with the phenomenon used for recognition (flux in the core).

When invented more than fifteen years ago, the method displayed a disadvantage due to the lack of ability to measure the voltage signals. Nowadays, the voltages are easily available for digital transformer protection terminals which makes this kind of relaying principles attractive.

Detection of external faults

In order to overcome dependability limitations inherent in the biased characteristic and enhance the performance of the differential relay, three approaches that modify the standard principle may be applied. They are:

- The DELTA-differential criterion which compares the increase of the differential current (with respect to its pre-fault value) with the adequate increase of the restraining current. The modified single slope bias characteristic is applied for such incremental signals.
- The sequence of events principle that enables distinguishing between internal and external fault currents under saturation of the CTs. This criterion acts as the trip suppressor and blocks the relay when the external fault hypothesis gets confirmed.
- The saturation detector that detects considerable saturation of the CTs. The result of detection is used to control on-the-fly the slope of the biased characteristic, which is increasing dependability of the differential relay.

Artificial Intelligence methods

Regardless of their digital implementation, numerical relays basically emulate their analog predecessors: they extract specified features of the signals such as magnitudes, active/reactive powers, impedance components, and compare the signals with appropriate pre-set or adaptable thresholds. Based on such comparisons they generate the tripping signal. The task of protective relaying is, however, to distinguish between internal faults and other conditions (pattern recognition), and consequently, to initiate or deny tripping (decision making). This brings the application of Artificial Intelligence methods as an alternative or improvement to the existing protective relaying functions.

Fuzzy Logic approach

The multi-criteria differential relay is a good example of the fuzzy logic approach to protective relaying. In this technique (Figure 6):

- The criteria signals such as amplitudes, harmonic contents, etc. are fuzzified in order to account for dynamic errors of the measuring algorithms. Thus, instead of real numbers, the signals are represented by fuzzy numbers. Since the fuzzification process provides a special kind of flexible filtering, faster measuring algorithms that speed up the operation of protective relays may be used.
- The thresholds for the criteria signals are also represented by fuzzy numbers to account for the lack of precision in dividing the space of the criteria signals between the tripping and blocking regions.
- The fuzzy signals are compared with the fuzzy settings. The comparison result is a fuzzy logic variable between the Boolean absolute levels of truth and false.
- Several relaying criteria are used in parallel. The criteria are aggregated by means of formal multi-criteria decision-making algorithms that allow the criteria to be assigned a weight according to the reasoning ability.
- The tripping decision depends on the multi-criteria evaluation of the status of a protected element (sound vs. faulty). Additional decision factors may include the amount of available information, or the expected costs of relay misoperation.

This relaying frame may be self-organizing, i.e. it may be automatically tuned prior to its installation using a large number of training cases, therefore resembling the Artificial Neural Network (ANN) based approach. The prior tuning results in an algorithm that is simple and traceable.

The Figure 7 presents a simplified block diagram of a fuzzy logic based differential relay for power transformers. The relay employs 12 protection criteria to restraint itself from tripping during inrush, over-excitation and external fault conditions. The operation of this scheme is illustrated using two cases particularly difficult from the standpoint of protective relaying.

The Figure 8 presents the differential and restraining currents for an internal turn-to-turn fault involving 16% of turns of the HV winding of the Yd11 140/10.4 kV two winding transformer. The fault occurs 50ms after switching-on of the transformer. Since the fault pattern is affected by the dominating inrush current, this case is very difficult and causes the traditional protection techniques to fail. The fuzzy logic scheme restraints itself from tripping during the inrush conditions and clears the fault 16ms after its inception regardless of the inrush pattern still present in the differential current.

The Figure 9 presents the differential and restraining currents for an internal fault at the terminals accompanied by extremely severe saturation of the CTs. The fuzzy logic relay clears the fault in 5ms.

Artificial Neural Network approach

Since ANNs can provide excellent pattern recognition, they are proposed by many researchers for implementation of power transformer relaying. The common application of the ANN technique to power transformer protection assumes (Figure 10):

- The ANN is fed by all the currents either in the phase, or in the differential-restraining coordinates. The sliding data widow, consisting of the recent and a few historical samples of the signals, is fed to the ANN.
- The output from the ANN encodes the tripping decision.
- The training patterns exposed to the ANN cover usually inrush conditions, internal and external faults. Only the selected data window positions are typically used for training.
- Additional pre- and post-processing may be applied.

The ANN approach can also be of either a global type or phenomena specific type. In the first case, the net is trained to differentiate internal faults from all the other phenomena. In the second case, it is trained to distinguish between internal faults and a specific non-internal fault pattern (inrush, for example). Also, the ANNs are proposed for certain auxiliary functions such as reconstruction of the secondary current waveforms distorted by saturation of the CTs.

The ANN based relays for power transformer show promising security and dependability.

The Figures 8 and 9 present the output from an ANN trained to protect the same transformer as in the example for the fuzzy logic scheme. The ANN is fed by half a cycle data window of the differential and restraining currents from all three phases. The net has 30 input neurons, 15 neurons in the hidden layer and 1 output neuron. The case from Figure 8 is tripped in 18ms and the case from Figure 9 is tripped in 12ms.

Future of transformer differential protection

Optical CTs and other sensors

The optical CTs have many essential advantages over the classical CTs. Lack of saturation effect, which will help avoiding many problems with differential relaying, is the primary benefit apart from excellent electric isolation and absence of any flammable materials such as oil. Present-day optical CTs are of two types: a bulk optical CT which uses a ring-like glass sensor and an optical fiber CT which uses an optical fiber as a sensor. The later kind displaying higher accuracy is of a particular interest. The efforts in this area focus on overcoming the problems associated with the linear birefringence inside the fibers in order to prevent decrease of sensitivity of the optical CT.

The Rogowski’s coil, a current measuring device that produces a low power output but offers many advantages over the classical CTs, is the another option for improving the operating conditions for transformer protection.

Also, completely new measuring devices are under research. The integrated measuring unit for both voltage and current is a good example. The operating principle of it is based on Poynting's theorem which defines how the electromagnetic energy in terms of the electric and magnetic field intensities at a point in space. The current is measured by sensing the tangential component of the magnetic field. The voltage is measured by sensing the radial component of the electric field in a well-defined region around the high-voltage conductor.

Advances in the area of measuring sensors will certainly contribute to the quality of power system protection.

Integration of monitoring and protection functions

As the monitoring techniques for power transformers mature in terms of reliability, they will be integrated with the protection functions. The relaying algorithms may use directly or indirectly the information provided by the transformer monitoring systems. The examples follow:

- By monitoring overvoltages and other conditions such as the number, duration and current magnitude of external faults, the transformer loss-of-life may be approximated and used to change adaptively the settings. The protective relays will be set to be more inclined to trip in the unclear situations as the protected transformer ages.
- The protection may be supported by the ultrasonic detectors of discharges.
- The new on-line stray inductance monitors based on the voltamperometric method may provide useful information to the relays about the shape of the transformer windings.
- Novel sensors of various types installed inside the tank may provide enormous amount of information for both monitoring and protection purposes.

Additional external measurements

As the substation systems integrate, virtually all the local measurements will be available for each of the relays installed. This enables the protective relays for power transformers to perform more involved analysis of the observed phenomena. It relates first of all to the voltage signals, but also other information may be efficiently utilized. For example, by watching the tripping orders of other relays and status of associated Circuit Breakers (CBs), the transformer protection may detect sympathetic inrush or inrush due to clearing an external fault.

For Further Reading

S.Horowitz and **A.G.Phadke,** *Power system relaying,* John Wiley & Sons, New York, 1995.

H.Ungrad, W.Winkler and **A.Wiszniewski,** *Protection techniques in electrical energy systems*, Marcel Dekker, New York, 1995.

IEEE Tutorial Course, *Advancements in microprocessor based protection and communication*, IEEE Catalog No.97 TP 120-0, July 1997.

M.M.Saha, B.Hillstrom, B.Kasztenny and **E.Rosolowski,** „A fuzzy logic based relay for power transformer protection", *ABB Review*, No.1/98, January 1998, pp.41-48.

M.Kezunovic, „A survey of neural net applications to protective relaying and fault analysis”, *Engineering Intelligent Systems*, Vol.5, No.4, December 1997, pp.185-192.

L. Kojovic, „Rogowski’s coil suit relay protection and measurement of power systems”, *IEEE Computer Applications in Power*, Vol.10, No.3, July 1997, pp.47-52.

Biographies

Bogdan Kasztenny (M'95, SM’98) received his M.Sc. (1989) and Ph.D. (1992) degrees, both with honors, from the Wroclaw University of Technology, Poland, where he is a faculty member of the Department of Electrical Engineering. In 1994 he was with the Southern Illinois University at Carbondale as a Visiting Professor. In the academic year 1997-98 Dr.Kasztenny was a Senior Fulbright Fellow at Texas A&M University, where currently he is an Associate Research Scientist. His research interests include power system protection, digital signal processing and real-time computer applications in power systems.

Mladen Kezunovic (S’77, M’80, SM’85) received his Dipl. Ing. degree from the University of Sarajevo, the M.S. and Ph.D. degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively. Dr.Kezunovic’s industrial experience is with Westinghouse Electric Corporation in the USA, and the Energoinvest Company in Sarajevo. He also worked at the University of Sarajevo. He was a Visiting Associate Professor at Washington State University in 1986-1987. He has been with Texas A&M University since 1987 where he is a Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for relay testing as well as application of intelligent methods to power system monitoring, control and protection. Dr.Kezunovic is a registered professional engineer in Texas.

Tables and Figures

<table>
<tr><th colspan="5">Table I. Problems related to protective relaying of power transformers</th></tr>
<tr><th>Disturbance</th><th>Measurement</th><th>Security</th><th>Dependability</th><th>Speed</th></tr>
<tr><td>Inrush</td><td rowspan="2">Accurate estimation of the 2nd and the 5th harmonics takes around one cycle. Off-nominal frequencies create extra measuring errors in harmonic ratio estimation</td><td rowspan="2">In modern power transformers, due to the magnetic properties of the core, the 2nd harmonic during inrush and the 5th harmonic during overexcitation may be very low jeopardizing relay security</td><td>The presence of higher harmonics does not indicate necessary an inrush. The harmonics may block a relay during severe internal faults due to saturation of the CTs</td><td rowspan="2">It usually takes one full cycle to reject the magnetizing inrush and stationary overexcitation hypotheses if an internal fault is not severe enough to be tripped by the unrestrained element</td></tr>
<tr><td>Overexcitation</td><td>The 5th harmonic may be present in internal fault currents due to saturation of the CTs, and due to rotor asymmetry of generators and/or power electronic devices</td></tr>
<tr><td>External faults</td><td rowspan="2">The measured currents display enormous rate of change and are often significantly distorted</td><td>External fault current when combined with ratio mismatch may generate a false differential signal.
The CTs, when saturated during external faults, may produce an extra differential signal</td><td>All the means of preventing false trippings during external faults reduce the dependability of the relay</td><td>The means of restraining the relay from tripping during external faults may limit the relay speed of operation</td></tr>
<tr><td>Internal faults</td><td>The internal fault current may be as low as few percent of the rated value. Attempts to cover such faults jeopardize relay security</td><td>The internal fault current may be as low as few percent of the rated value. The security demands under inrush, overexcitation and external faults limit the relay dependability</td><td>The means of restraining the relay from tripping during inrush, overexcitation and external faults limit the relay speed of operation</td></tr>
</table>

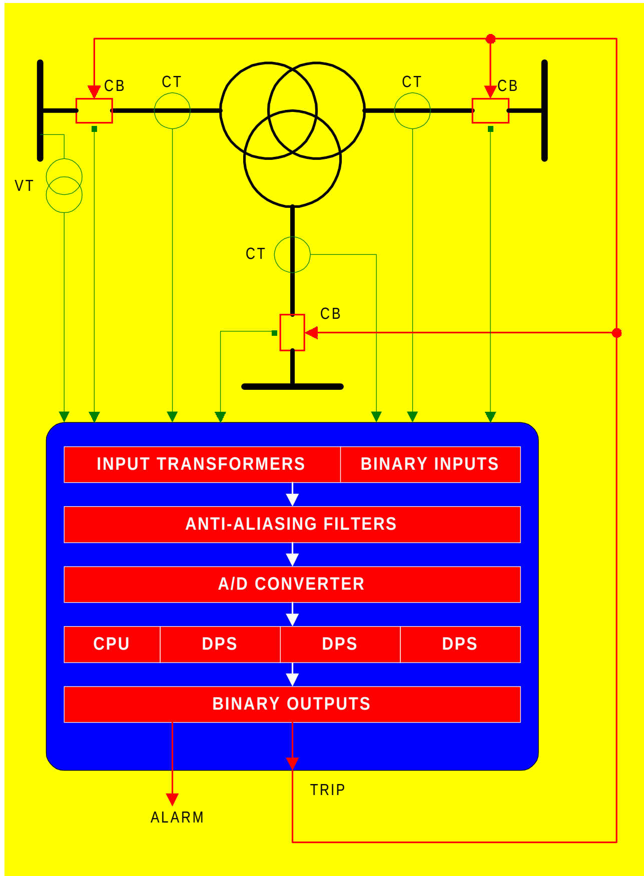

Figure 1. Hardware structure of a digital relay for power transformers.

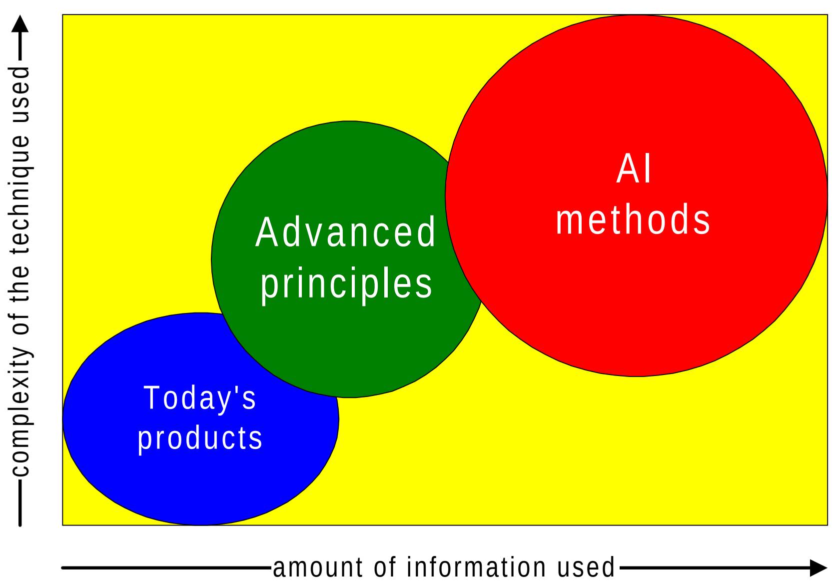

Figure 2. Different approaches to power transformer protection.

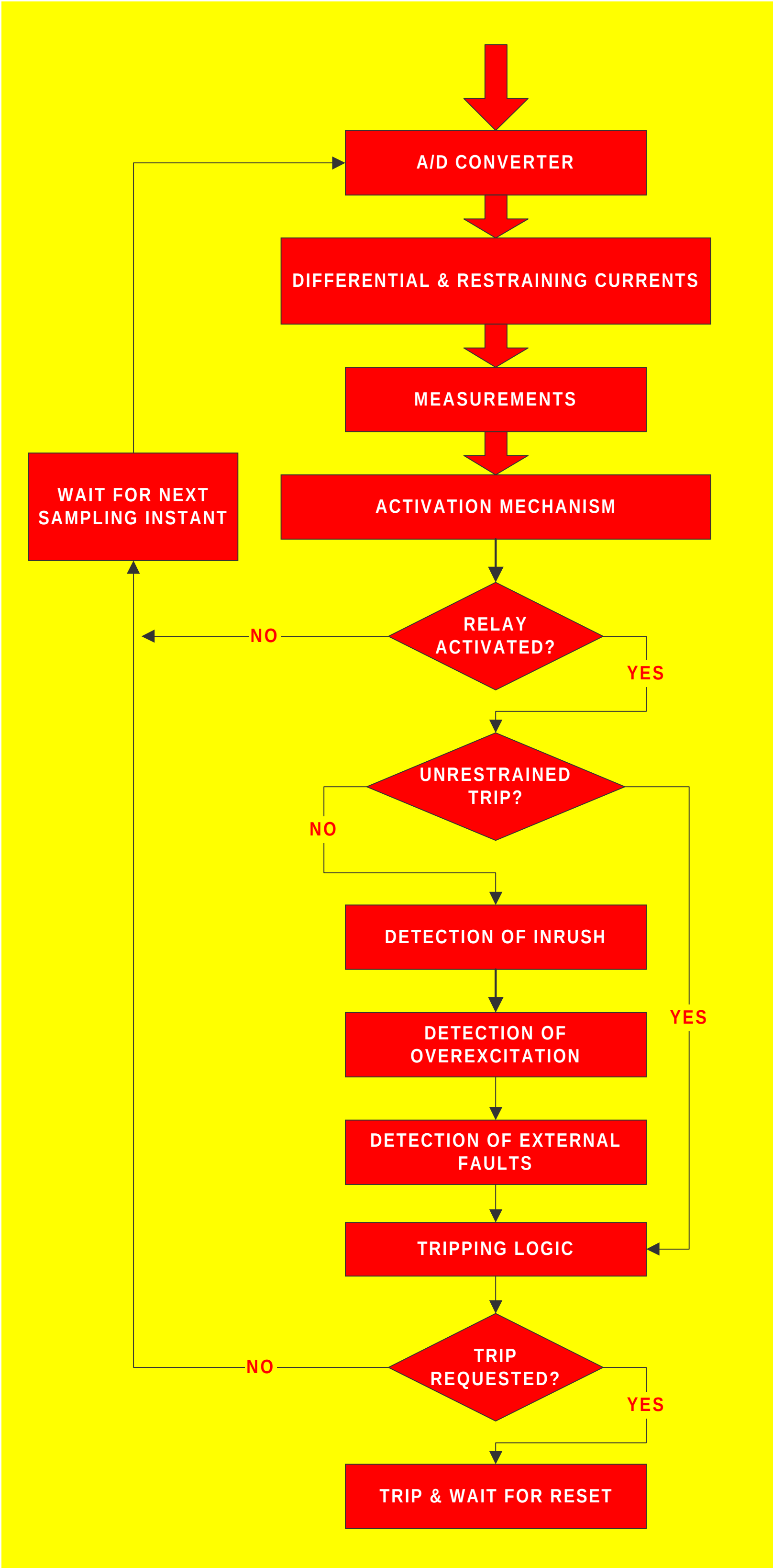

Figure 3. Simplified flow chart of the logic for digital differential relay for power transformers.

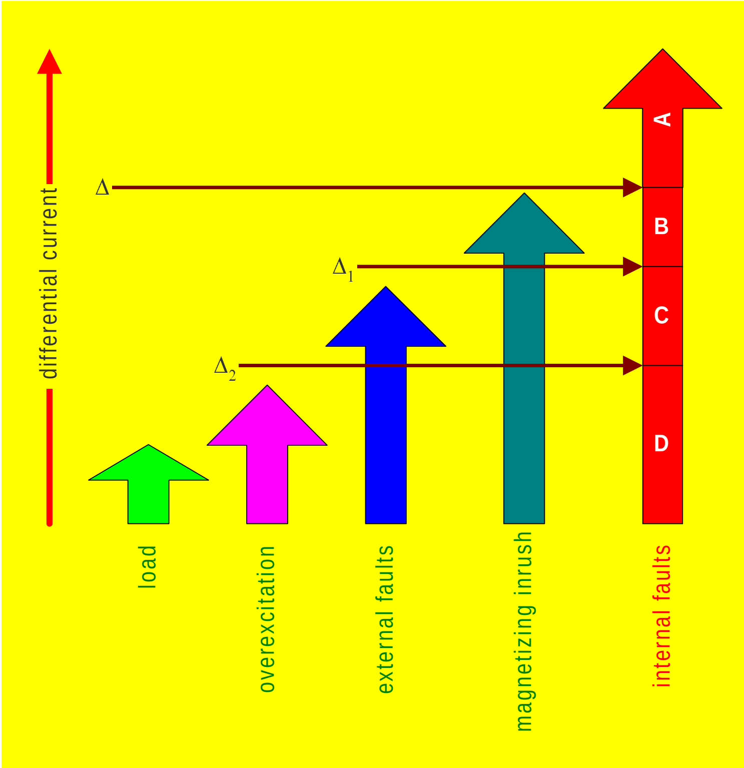

Figure 4. Illustration of the multi-setting overcurrent principle.

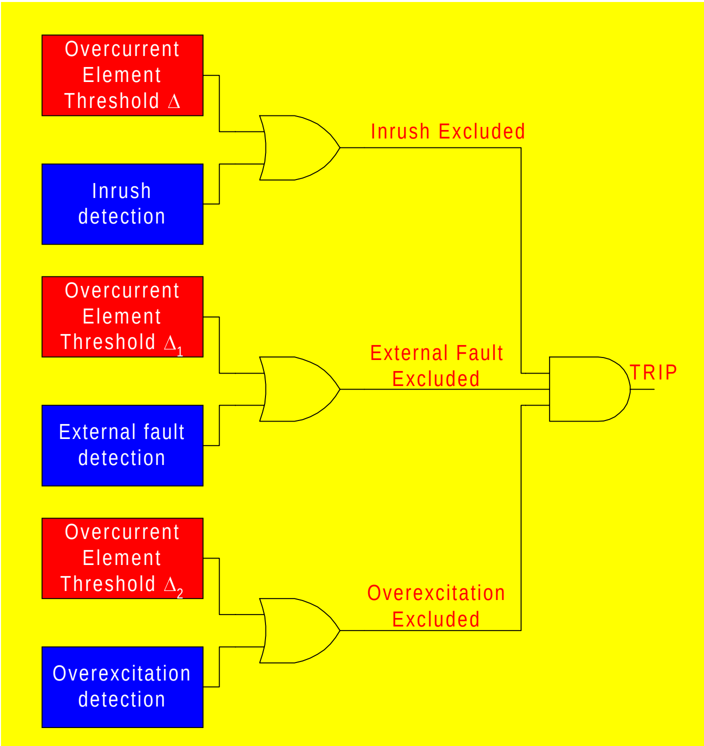

Figure 5. Application of the overcurrent principle with multiple settings.

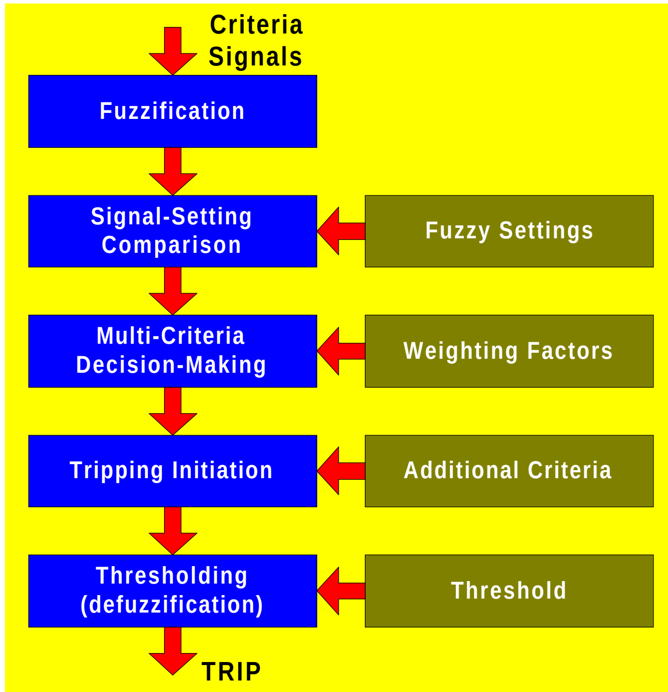

Figure 6. Simplified flow chart of the Fuzzy Logic protective relay.

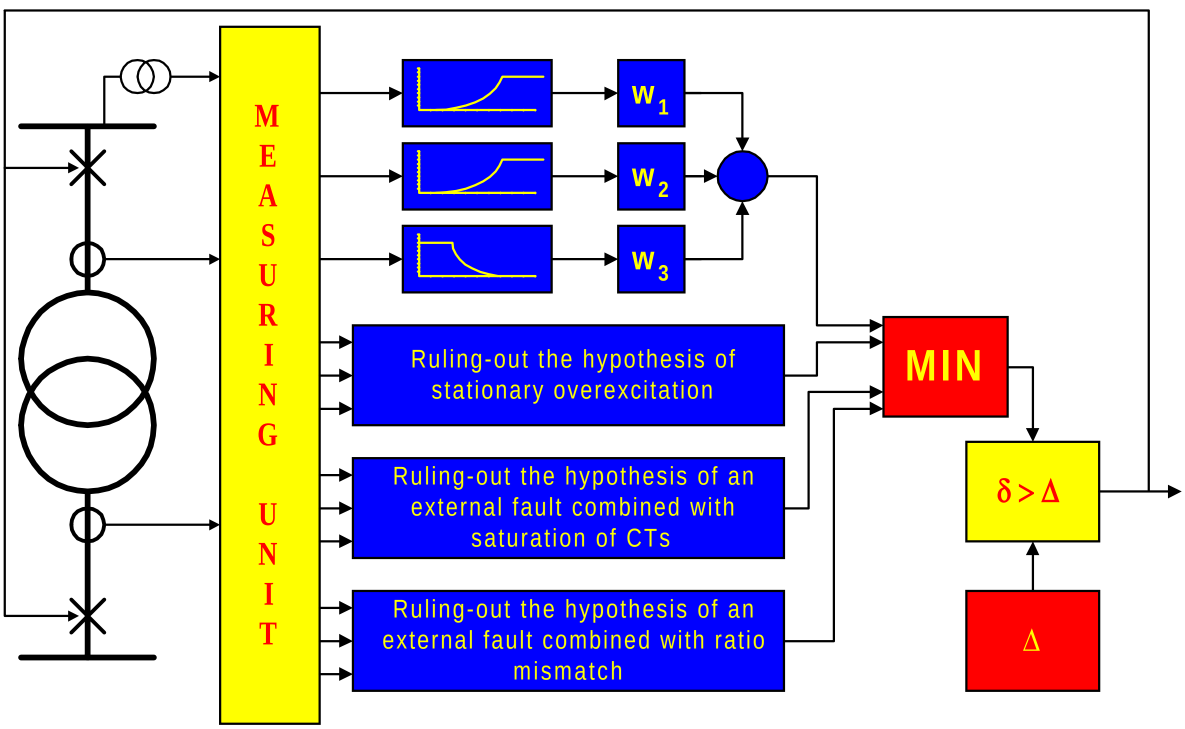

Figure 7. Simplified block diagram of the Fuzzy Logic differential relay for power transformers.

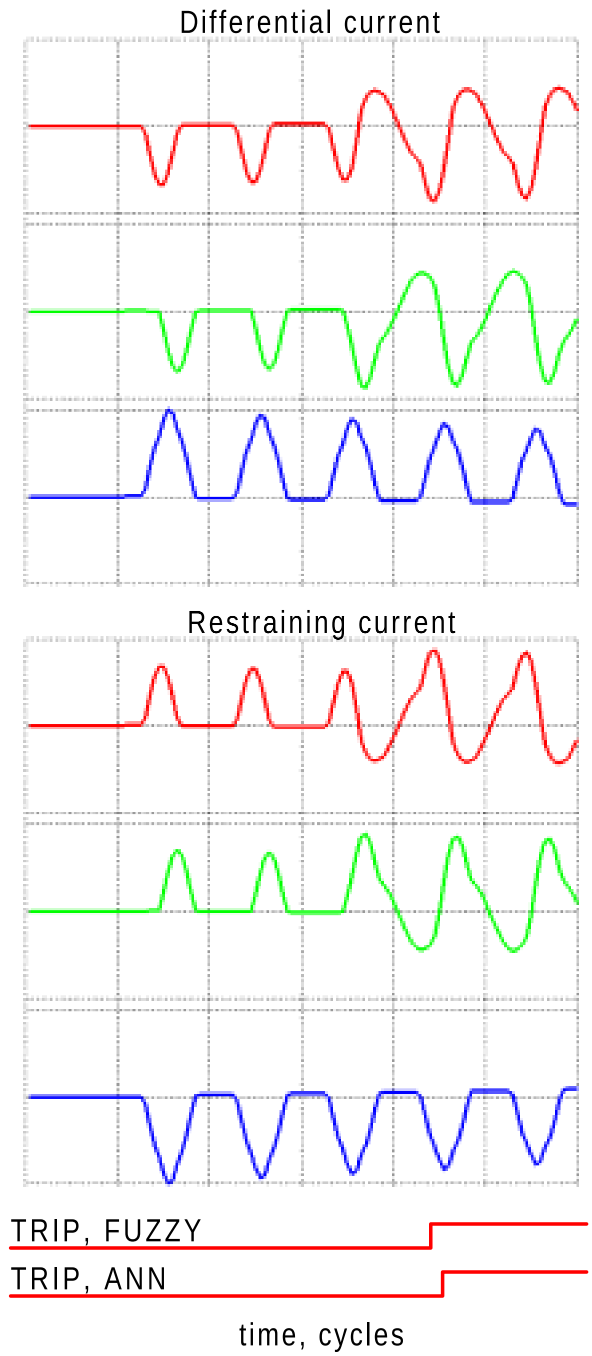

Figure 8. The differential and restraining currents during internal fault occurring in the course of transformer energization, and the trip signals of the fuzzy and ANN based transformer relays.

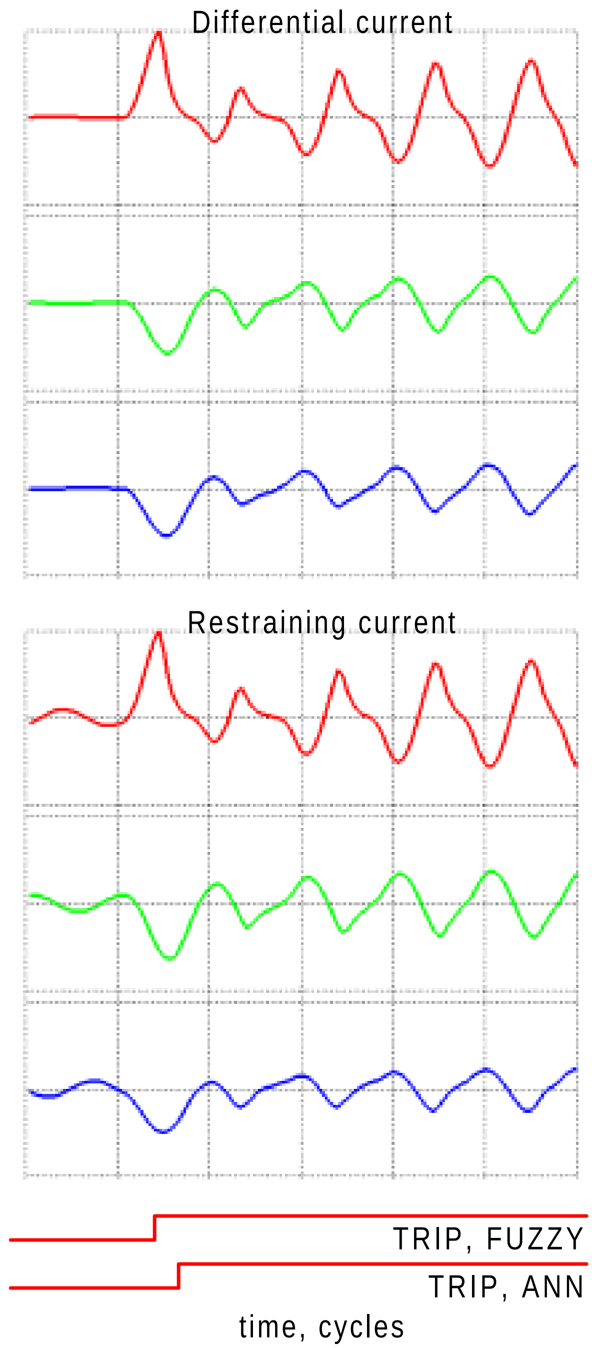

Figure 9. The differential and restraining currents during an internal fault with deep saturation of the CTs, and the trip signals of the fuzzy and ANN based transformers relays.

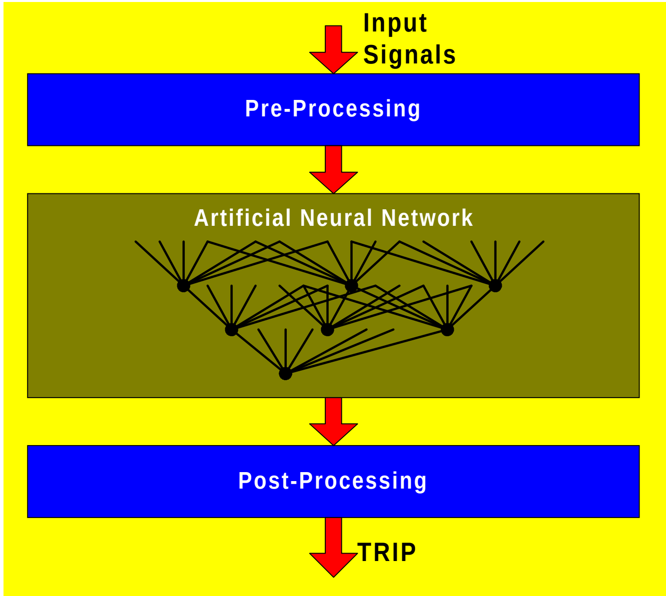

Figure 10. Application of the ANN technique to protective relaying.

<table>
<tr><th colspan="5">Table II. Improvements area resulting from new protection techniques for power transformers</th></tr>
<tr><th></th><th>Inrush</th><th>Overexcitation</th><th>External faults</th><th>Saturation of CTs</th></tr>
<tr><td>Advanced numerical methods</td><td colspan="2">Considerable improvement in relay security especially if the voltage signals are available. The speed of operation during internal faults is, however, difficult to improve.</td><td>Considerable improvement in dependability owing to the principles such as the DELTA-differential criterion for external faults.</td><td>Saturation detectors can enhance both the dependability and security. They have, however, difficulties during inrush currents both with and without saturation of the CTs.</td></tr>
<tr><td>Artificial Neural Networks</td><td colspan="3">The pattern recognition property of ANNs enables distinguishing the internal fault waves from all the other disturbances with high accuracy. This includes correct treatment of the cases with saturation of the CTs.</td><td>ANNs may be used as stand alone tools to mitigate the problem of saturation of the CTs - either as saturation detectors or algorithms reconstructing the primary waves.</td></tr>
<tr><td>Fuzzy Sets and Logic</td><td colspan="3">The multi-criteria decision making approach allows employing many different protection principle for inrush, overexcitation and external faults in parallel. It enables one to improve both security and dependability of the relay.</td><td>The fuzzy filtering may be a partial remedy for measuring errors caused by the saturated CTs.</td></tr>
<tr><td>Optical CTs</td><td>The optical CTs allow avoiding problems associated with CT saturation during inrush. They are not, however, helping detecting the magnetizing inrush.</td><td>No improvement</td><td colspan="2">Significant improvement by avoiding CT saturation (a source of a false differential signal). The optical CTs may improve both dependability and security of the relay.</td></tr>
<tr><td>Extra External Measurements</td><td colspan="2">External measurements helping tide an unknown transient that triggered the relay with the source in the substation. This helps preventing false trippings during both magnetizing inrush and stationary overexcitation conditions.</td><td>Communicating with other relays may help the transformer relay to distinguish between internal and external faults.</td><td rowspan="2">Detecting internal faults based on more information than just the differential signal can enhance dependability.</td></tr>
<tr><td>Extra Internal Measurements</td><td colspan="2">Direct detecting of core saturation may significantly enhance the relay security.</td><td>Directly detecting internal faults (such as discharges) may enhance relay dependability.</td></tr>
</table>