Digital Relays Improve Protection of Large Transformers

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Large power transformers belong to a class of very expensive and vital components of 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 damage is minimized. The costs associated with repairing a damaged transformer may be very high. An unplanned outage of a power transformer can cost electric utilities millions of dollars. Consequently, it is of great importance to minimize the frequency and duration of unwanted outages. Accordingly, high demands are imposed on power transformer protective relays. 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 the relaying task easy. Protection of large power transformers is one of the most challenging problems 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 of this will change the practice for power transformer protection. This article briefly reviews the state of the art, but is primarily devoted to discussion of new approaches and future directions in digital relaying for power transformers.

Transformer Differential Protection

Figure 1 presents the 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 terminals of the protected transformer by computing and monitoring a differential (unbalance) current. The nonzero value of the differential signal indicates an internal fault. However, transformer operating conditions may introduce problems, as presented in Table 1.

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

- Principles applied in today's products basically use current signals and limit analysis to the fundamental frequency components and higher harmonics of those signals.
- Advanced numerical principles already invented but not broadly implemented use more information, including voltage signals as well as signal features other than just harmonics.
- AI approaches already suggested but not sufficiently investigated tend to utilize all available information.

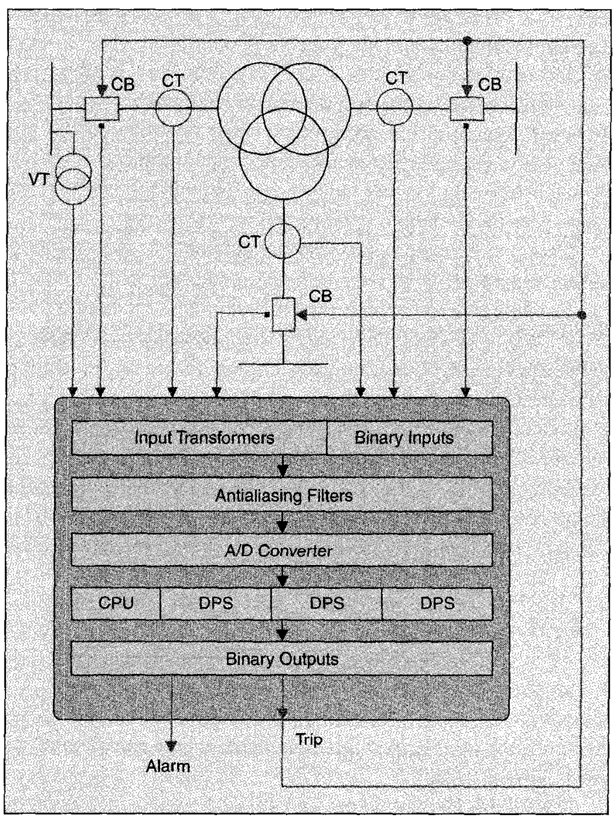

Figure 1. Hardware structure of a digital relay for power transformers

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Table 1. Problems related to protective relaying of power transformers

Disturbance	Measurement	Security	Dependability	Speed
Inrush	Accurate estimation of the second and fifth harmonics takes around one cycle. Off-nominal frequencies create extra measuring errors in harmonic ratio estimation.	In modern power transformers, due to magnetic properties of the core, the second harmonic during inrush and the fifth harmonic during over-excitation may be very low, jeopardizing relay security.	Presence of higher harmonics does not necessarily indicate an inrush. Harmonics may block a relay during severe internal faults due to saturation of CTs.	Usually takes one full cycle to reject magnetizing inrush and stationary over-excitation hypotheses if an internal fault is not severe enough to be tripped by the unrestrained element.
Over-Excitation			The third harmonic may be present in internal fault currents due to saturation of CTs and rotor asymmetry of generators and/or power electronic devices.	
External Faults	Measured currents display an enormous rate of change and are often distorted significantly.	External fault current, when combined with ratio mismatch, may generate a false differential signal. CTs, when saturated during external faults, may produce an extra differential signal.	All means of preventing false trippings during external faults reduce the dependability of relay.	Means of restraining the relay from tripping during external faults may limit the speed of relay operation.
Internal Faults		An internal fault current may be as low as a few percent of the rated value. Attempts to cover such faults jeopardize relay security.	The internal fault current may be as low as a few percent of rated value. Security demands under inrush, over-excitation, and external faults limit relay dependability.	Means of restraining the relay from tripping during inrush, over-excitation, and external faults limit the speed of relay operation.

The numerical complexity of an algorithm is the price to pay for processing more information.

Classical Restraining Criteria

Figure 2 presents a simplified flowchart of the logic of a digital differential relay for power transformers. Within this frame, the second or higher harmonic is used to prevent false tripping during magnetizing inrush conditions; the fifth harmonic is commonly used to restrain the differential relay during stationary over-excitation conditions, while the biased percentage characteristic is used to prevent false tripping during external faults.

This traditional approach may not be able to deal with certain problems, as revealed in Table 1.

Advanced Numerical Restraining Criteria

New operating principles have been invented for digital relays. They result in more involved numerical operations rather then just in a simple increase of the number of functions known from the era of electromechanical relays and bring certain improvements in protective relaying for power transformers, as shown in Table 2. These principles can be classified between the global approaches and phenomena-specific approaches.

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 latter into magnetizing inrush, over-excitation, and external faults.

Model Methods. This family of approaches solves, online, a mathematical model of a fault-free transformer. Either certain parameters of the model are computed assuming the measured signals, or a 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 calculated and measured signals enables the relay to perform the classification. These approaches call for voltages and currents at all terminals to be measured.

Differential Power Method. Another relaying principle uses 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 of the transformer's terminals. This approach calls for measuring voltages at all terminals but pays back by enabling the avoidance of 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 internal active power losses, both in copper and in iron.

In addition, having active power available, this 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.

Multisetting Overcurrent Principle. 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.

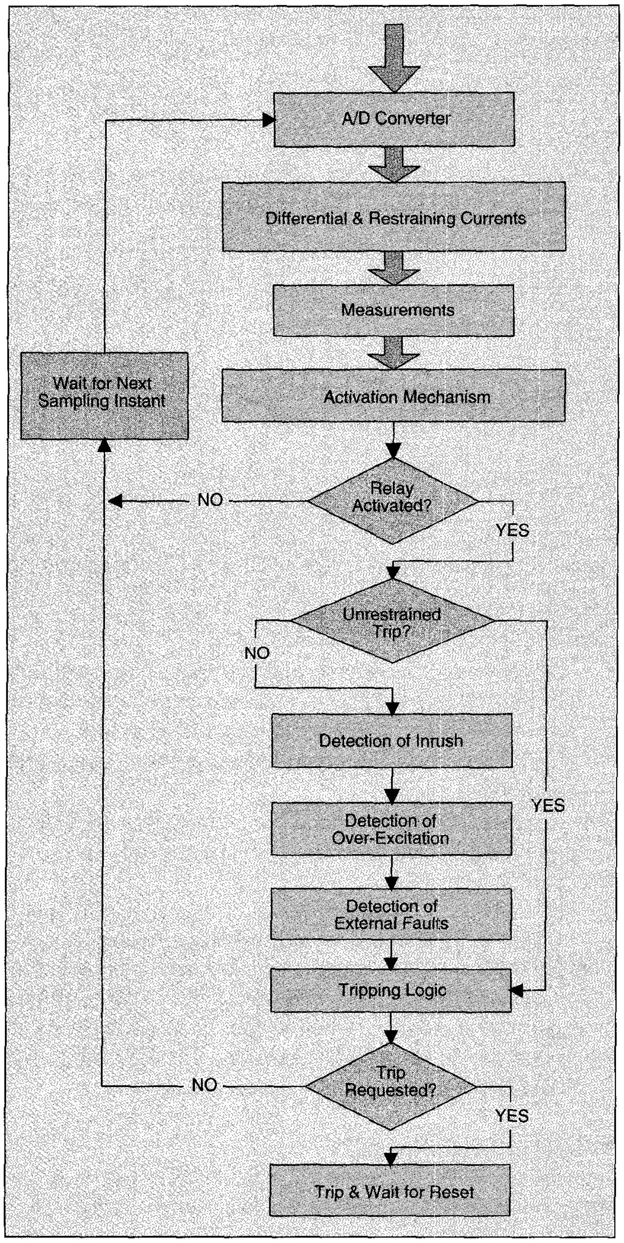

Figure 2. Logic for a digital differential relay for power transformers

Figure 3 presents amplitudes of the differential currents under the load, over-excitation, external fault, magnetizing inrush, and internal fault conditions. The classical unrestrained differential overcurrent element must apply the threshold Δ set above the maximum noninternal fault current (Figure 3). If so, internal faults denoted as class A are tripped by the overcurrent element, while all other faults of classes B through D must wait to be detected by the restrained element.

However, the internal faults of class B may be distinguished from external faults and over-excitation phenomena by the overcurrent element working with the second lower threshold D1 (Figure 3). If so, the internal faults of class A are detected by the overcurrent principle with the threshold D. The internal faults of class B are detected by the overcurrent element with the threshold D1 if the inrush hypothesis is rejected by the other relaying principle, such as the second harmonic restraint. The external fault and over-excitation conditions may not be checked at all, since they are ruled out by the overcurrent element (D1). Similar reasoning applies to the faults of classes C and D.

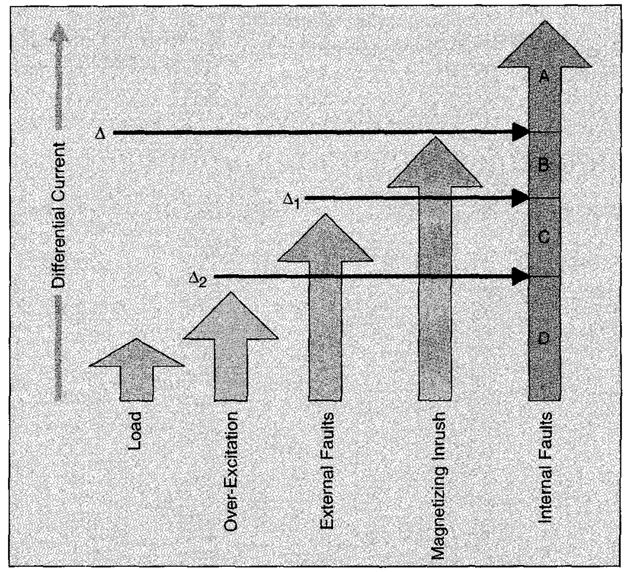

Figure 3. Multisetting overcurrent principle

The principle of the multisetting overcurrent element is implemented as shown in Figure 4 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 internal faults with medium levels of fault current (classes B and D in Figure 3). This approach enhances dependability by speeding up the operation and covering low-current internal faults.

Phenomena-Specific Approaches

By *phenomena-specific approach*, we mean a relaying algorithm that restrains the relay from tripping in only one particular noninternal 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 inrush and over-excitation conditions based on the calculated flux in the core. As its advantage, this approach ties 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 15 years ago, this method

Table 2. Improvement areas resulting from new protection techniques for power transformers

Technique	Inrush	Over-Excitation	External Faults	Saturation of CTs
Advanced Numerical Methods	Considerable improvement in relay security, especially if voltage signals are available. Speed of operation during internal faults is difficult to improve.		Considerable improvement in dependability from principles such as the delta-differential criterion for external faults.	Saturation detectors can enhance dependability/security but have difficulty during inrush currents with/without saturation of CTs.
Artificial Neural Networks	The pattern recognition property of ANNs enables distinguishing internal fault waves from all other disturbances with high accuracy. This includes correct treatment of cases with saturation of CTs.			May be used as stand-alone tools to mitigate saturated CTs, as saturation detectors or algorithms reconstructing primary waves.
Fuzzy Sets and Logic	The multicriteria decision-making approach allows employing many different protection principles for inrush, over-excitation, and external faults in parallel. It enables improvement of relay security and dependability.			Fuzzy filtering may be a partial remedy for measuring errors caused by saturated CTs.
Optical CTs	Enable avoidance of problems associated with CT saturation during inrush, but do not help detect magnetizing inrush.	No improvement	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.	
Extra External Measurements	Help tie an unknown transient that triggered the relay with the source in the substation. This helps prevent false trippings during both magnetizing inrush and stationary over-excitation conditions.		Communicating with other relays may help the transformer relay distinguish between internal and external faults.	Detection of internal faults based on more information than just the differential signal can enhance dependability.
Extra Internal Measurements	Direct detection of core saturation may significantly enhance relay security.		Direct detection of internal faults (such as discharges) may enhance relay dependability.	

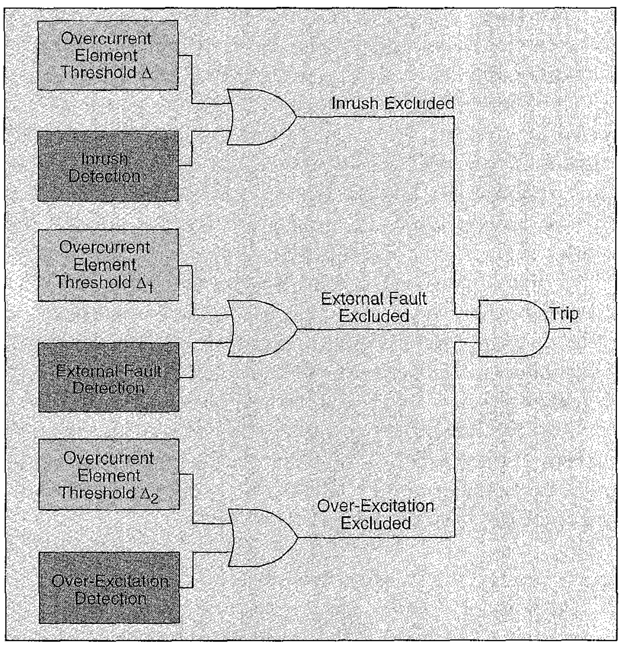

Figure 4. Application of the overcurrent principle with multiple settings

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 principle 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:

- Delta-differential criterion, which compares the increase of the differential current (with respect to its prefault value) with the adequate increase of the restraining current. The modified single slope bias characteristic is applied for such incremental signals.
- Sequence-of-events principle, which 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.
- Saturation detector, which detects considerable saturation of the CTs. The result of the detection is used to control, on-the-fly, the slope of the biased characteristic, which increases the dependability of the differential relay.

Artificial Intelligence

Regardless of their digital implementation, numerical relays basically emulate their analog predecessors. They extract specified features of the signals (such as magnitude, active/reactive power, impedance components) and compare the signals with appropriate preset 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 Applications

The multicriteria differential relay is a good example of the fuzzy logic approach to protective relaying. In this

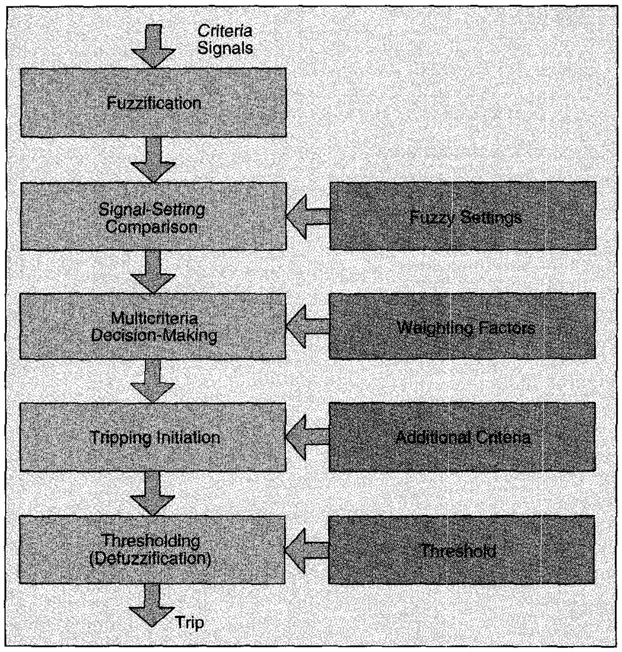

Figure 5. Fuzzy logic protective relay

technique (Figure 5):

- 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.
- 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.
- Fuzzy signals are compared with fuzzy settings. The comparison result is a fuzzy logic variable between the Boolean absolute levels of true and false.
- Several relaying criteria are used in parallel. The criteria are aggregated by means of formal multicriteria decision-making algorithms that allow the criteria to be assigned a weight according to the reasoning ability.
- The tripping decision depends on the multicriteria evaluation of the status of a protected element (sound versus 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. Prior tuning results in an algorithm that is simple and traceable.

Figure 6 presents a simplified block diagram of a fuzzy-logic-based differential relay for power transformers. The relay employs 12 protection criteria to restrain itself from tripping during inrush, over-excitation, and external fault conditions. The operation of this scheme is illustrated using two cases (Figures 7 and 8) that are particularly difficult from the standpoint of protective relaying.

Figure 7 presents differential and restraining currents for an internal turn-to-turn fault involving 16 percent of turns of the HV winding of the Y/delta 140/10.4 kV two-winding transformer. The fault occurs 50 ms after switching on 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 restrains itself from tripping during the inrush conditions and clears the fault 16 ms after its inception, regardless of the inrush pattern still present in the differential current.

Figure 8 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 5 ms.

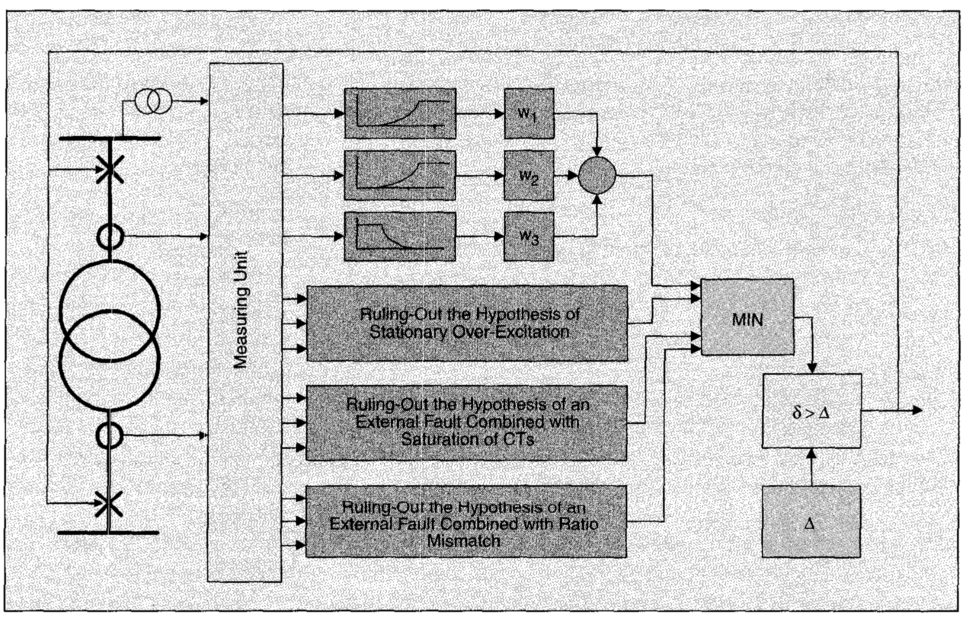

Figure 6. Fuzzy logic differential relay for power transformers

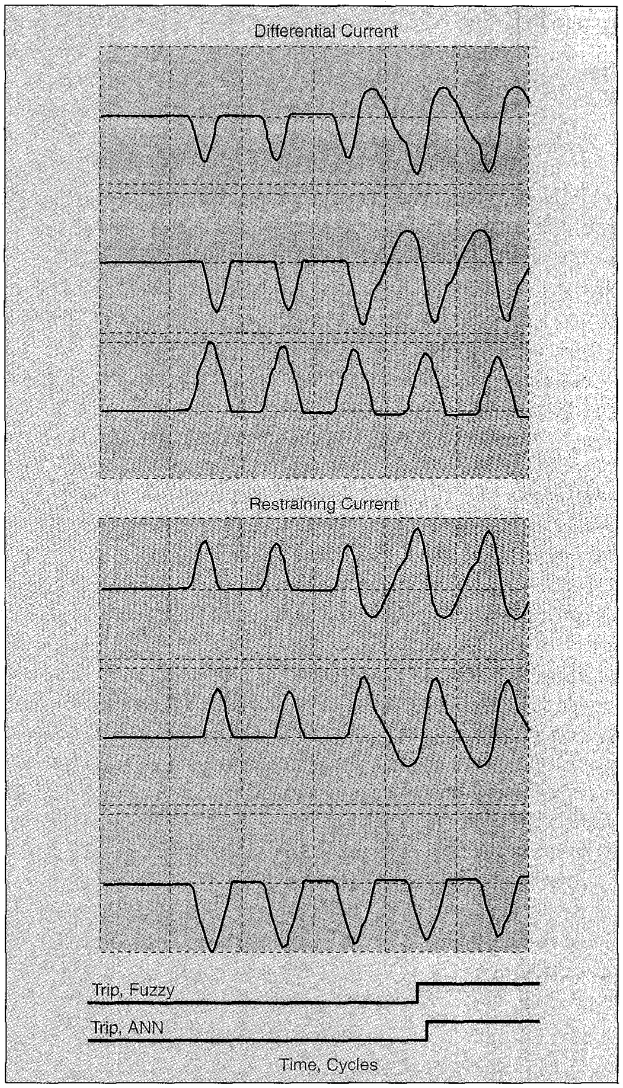

Figure 7. Differential and restraining currents during an internal fault occurring in the course of transformer energization, and trip signals of the fuzzy-logic and ANN based transformer relays

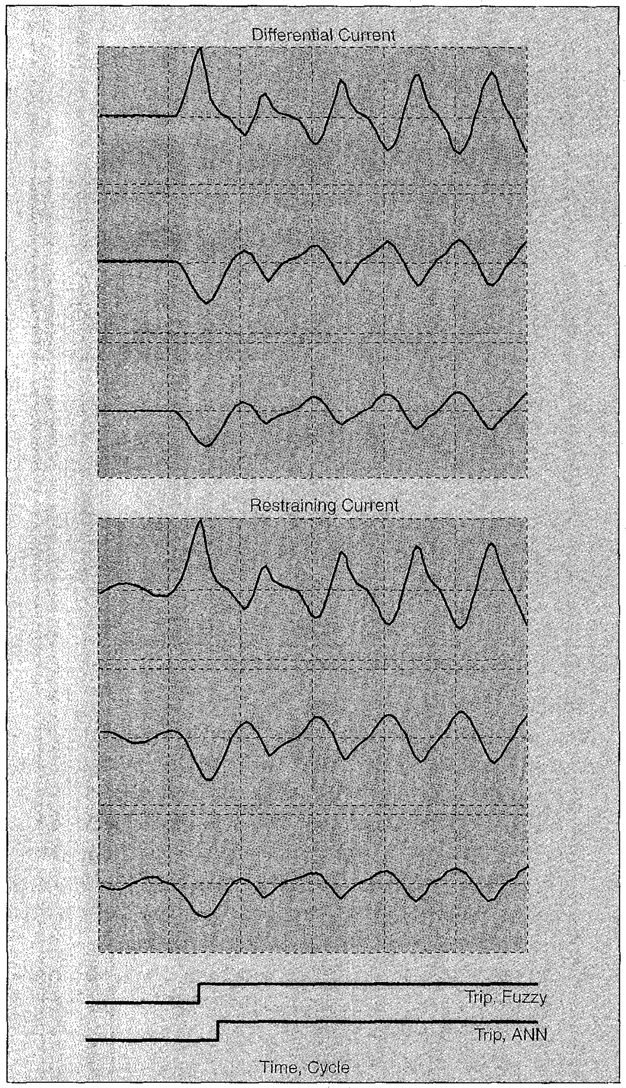

Figure 8. Differential and restraining currents during an internal fault with deep saturation of the CTs, and trip signals of the fuzzy-logic and ANN based transformers relays

ANN Applications

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:

- The ANN is fed by all currents either in the phase or differential-restraining coordinates. The sliding data widow, consisting of recent and a few historical samples of the signals, is fed to the ANN.
- Output from the ANN encodes the tripping decision.
- Training patterns exposed to the ANN usually cover inrush conditions, internal faults, and external faults. Only the selected data window positions are typically used for training.
- Additional preprocessing and postprocessing 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 other phenomena. In the second case, it is trained to distinguish between internal faults and a specific noninternal fault pattern (inrush, for example). Also, ANNs are proposed for certain auxiliary functions, such as reconstruction of the secondary current waveforms distorted by saturation of the CTs.

ANN-based relays for power transformers show promising security and dependability.

Figures 7 and 8 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 7 is tripped in 18 ms, and the case from Figure 8 is tripped in 12 ms.

Future of Transformer Differential Protection

With substation integration and the application of new sensors, more measurements will be available to transformer relays.

Optical CTs and Other Sensors

Optical CTs have many essential advantages over the classical CTs. Lack of the saturation effect, which will help avoid 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 displays higher accuracy and is of particular interest. Efforts in this area focus on overcoming the problems associated with linear birefringence inside the fibers in order to prevent decreased sensitivity of the optical CT.

The Rogowski 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 being researched. 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 electromagnetic energy in terms of the electric and magnetic field intensifies at a point in space. Current is measured by sensing the tangential component of the magnetic field. Voltage is measured by sensing the radial component of the electric field in a well-defined region around the HV conductor.

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

Integration of Monitoring and Protection Functions

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

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

Additional External Measurements

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

For Further Reading

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Biographies

Bogdan Kasztenny received his MS and PhD, both with honors, from the Wroclaw University of Technology, Poland, where he is a faculty member in 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, he was a Senior Fulbright Fellow at Texas A&M University, where he is currently an associate research scientist. His research interests include power system protection, digital signal processing, and real-time computer applications in power systems. He is a senior member of the IEEE.

Mladen Kezunovic received his Dipl. Ing. from the University of Sarajevo and his MS and PhD from the University of Kansas, all in electrical engineering. His industrial experience is with Westinghouse Electric Corporation and the Energoinvest Company (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. He is a senior member of the IEEE and a registered professional engineer in Texas.