

A fuzzy logic based relay for power transformer protection

In accordance with an R&D agreement between ABB and the University of Wrocław, Poland, a multi-criteria protective relay based on fuzzy sets and logic has been developed for use with three-phase power transformers. Twelve criteria are used to stabilize the relay. The protection scheme features internal functions and coefficients which allow off-line self-adjustment of the relay prior to installation. Three unique procedures for the settings make the relay self-organized. Results of tests show significant gains in sensitivity and selectivity for the self-organized relay compared with traditional approaches to the problems of protective relaying.

Protection schemes employing the differential relaying principle exhibit certain limitations in applications with power transformers. This is because the detection of a differential current does not clearly distinguish between internal faults and other possible conditions. Among the phenomena most likely to upset the current balance and cause the relay to malfunction are inrush magnetizing currents, stationary overexcitation of a core, external faults in the presence of current transformer (CT) saturation, and/or CT and power transformer ratio mismatch.

To mitigate these problems, a number of more or less reliable protection criteria have been developed which support the traditional biased differential characteristic in combination with 2nd and 5th harmonic restraints [1,2]. They include the Δ -differential principle, direct waveshape identification, protective algorithms based on electromagnetic equations of the protected transformer,

and adaptive approaches, to name just some of the recognition techniques introduced in recent decades. The measuring units of contemporary relays are also improved by the use of Fourier methods, Kalman filtering techniques and optimal state observers.

Research work in the above areas naturally focuses on a multi-criteria approach to power transformer relaying. One result of this work has been the development of a general fuzzy logic based

Dr. Murari M. Saha

Birger Hillström

ABB Network Partner AB

Dr. Bogdan Kasztenny

Dr. Eugeniusz Rosolowski

Technical University of Wrocław

platform for a multi-criteria transformer relay that introduces several new artificial intelligence (AI) related concepts [3–5].

A protective device with AI features offers enormous potential for optimization. It has a number of internal coefficients, functions and thresholds [3, 4] that can be adjusted in order to tune a relay to a protected element and improve the quality of the protection. However, no recommendations exist for an approach of this kind; neither is any practical experience available that could be used to set the internal relay parameters mentioned.

Research was therefore undertaken to resolve this problem. In the following, a look is taken at a 12-criteria Fuzzy Logic protective Relay (FLR) for power transformers and at the unique algorithms used for its automatic, off-line self-adjustment prior to installation.

Protection criteria for power transformers

The following modes of power transformer operation have been identified from the point of view of protective relaying:

- a Inrush conditions
- b Stationary overexcitation of a transformer core
- c External fault combined with CT saturation
- d External fault or high load current without CT saturation, but with mismatched ratios of the transformer and CTs
- e Internal fault
- f Normal operation

Usually, it is assumed that the protected transformer leaves the ‘normal operation’ mode (f) when its relay is activated. Here, as is normally the case, pick-up of the relay will be assumed to be based on the instantaneous overcurrent principle.

When activated, the relay issues the tripping command provided that, based on the information carried by the relaying signals, it is capable of rejecting the non-internal fault hypotheses (a–d). This approach is convergent with common practice in transformer protective relaying whereby, instead of confirming an internal fault, the relay rules out the remaining suppositions.

Twelve protection criteria

Twelve protection criteria, $C_1 - C_{12}$, have been identified for power transformers [3]. In the following, each individual criterion is described and the item of knowledge it covers formalized by the definition of a signal for it. The shape of these signals is ‘high’ for internal faults and ‘low’ for other conditions, or vice versa (for criteria $C_1, C_2, C_4, C_9, C_{10}, C_{11}, C_{12}$ high values call for tripping, while for C_3, C_5, C_6, C_7, C_8 low values call for tripping). The processing of the signals to obtain the tripping command is based on fuzzy logic laws.

Case a

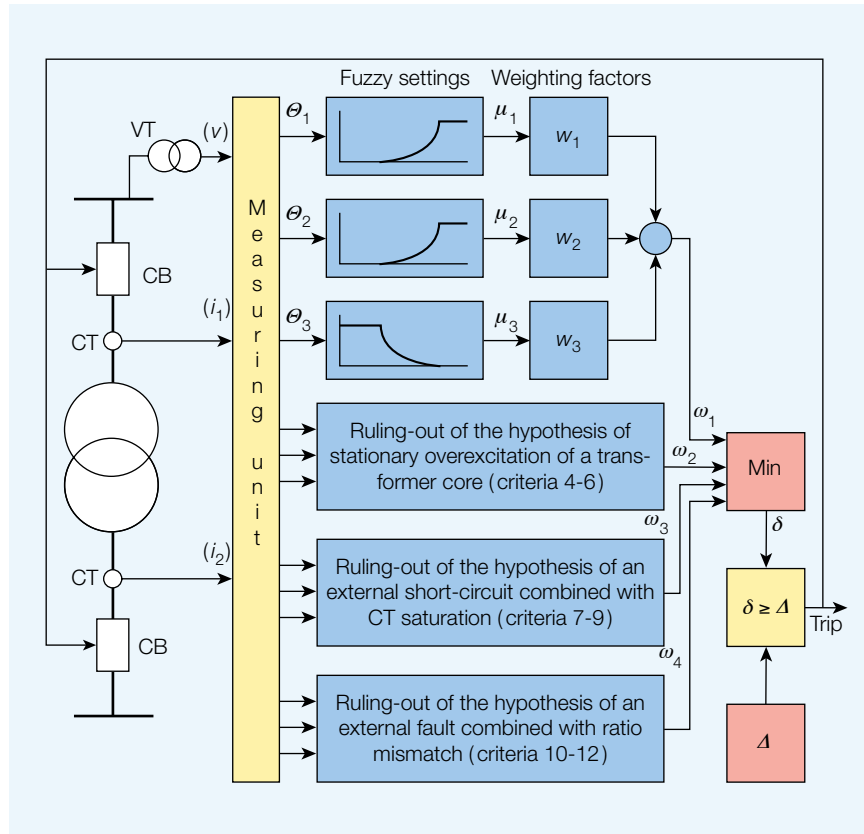
Magnetizing inrush may be ruled out if:

Criterion C_1 : the value of the differential current is higher than the highest expected inrush current level (*instantaneous overcurrent principle*).

The question to be answered here is whether the absolute value of a sample of the differential current, its fundamental component amplitude, or even a combination of the two, should be used. For the purpose of this discussion, the amplitude will be used as the criteria signal θ :

$$\theta_{1(n)} = I_{\Delta 1(n)} \tag{1}$$

$I_{\Delta i}$ Amplitude of the i th harmonic of the differential current ($i = 1$ is the fundamental frequency component)



Simplified block diagram of a fuzzy logic based relay for power transformer protection

1

- δ Fuzzy tripping support
- μ_{1-3} Continuous logic signals
- ω_{1-4} Inrush signals
- Δ Tripping threshold
- θ_{1-3} Criteria signals
- CB Circuit-breaker
- CT Current transformer
- VT Voltage transformer

- θ_k Criteria signal ($k = 1-12$)
- n Discrete time index

The protective relay is assumed to be a complex of three identical sub-relays, one for each phase. Thus, θ_1 has to be computed for all three phases (the phase index is omitted to simplify the notation). For two of the presented criteria (C_2 and C_{11}), however, all three phases are checked simultaneously.

Only the sample definition of θ_1 is given here; details of the rest of the criteria signals may be found in [3].

Criterion C_2 : certain fragments of the waveshapes of the differential currents in all three phases are not shown (sections

lasting not less than $\frac{1}{6}$ of a cycle) when the levels of both the current and its derivative are close to zero (*direct wave-shape identification*).

The differential current may also exhibit such periods during severe internal faults accompanied by current transformer saturation. However, when observed in all three phases they are shifted in time, while during inrush they are perfectly synchronized (**7a**, **8a**).

Criterion C_3 : the second harmonic in the differential current is below about 10–15% of its fundamental (*2nd harmonic restraint*).

Case b

Stationary overexcitation of a transformer core may be ruled out if:

Criterion C₄: the level of the differential current is higher than in cases of transformer overexcitation (*overcurrent principle*).

The overcurrent criterion is repeated here. It should be noted, though, that C₄ is dedicated to stationary overexcitation, while C₁ recognizes inrush conditions. The setting for C₄ is usually much lower than for C₁. Thus, for certain internal faults C₄ is able to exclude overexcitation, while C₁ is not able to rule out inrush. However, in the multi-criteria approach, the inrush hypothesis may be excluded because of some other criteria, enabling the tripping command to be sent. It is in this way that multi-stage analysis of the differential current improves the relay.

Criterion C₅: the integral of the terminal voltage amplitude for half a cycle, which reflects the flux in a transformer core, is below the saturation level (*simplified flux based restraint*).

Criterion C₆: the level of the 5th harmonic in the differential current is below about 30 % of its fundamental (*5th harmonic restraint*).

Case c

An external short circuit combined with saturation of CTs may be excluded if:

Criterion C₇: the high value of the through-current does not exist during the cycle before the high differential current value was detected (*sequence of events*).

This criterion is based on the observation that CTs usually transform accurately for at least 1/4 of a cycle after the fault inception before becoming saturated.

Criterion C₈: the level of the 2nd harmonic in the differential current is below about 20 % of the fundamental component.

Criterion C₉: the differential current is greater than the highest current during an external short-circuit in the pres-

ence of CT saturation (*overcurrent principle*).

Case d

An external fault or high load current without CT saturation may be ruled out if:

Criterion C₁₀: the differential current is much higher than the through-current (*biased differential characteristic*).

To gain sensitivity, the Δ-differential rule is applied [3]. By subtracting the relevant pre-fault values, this approach considers only the fractions of the differential and through-currents caused by a fault.

Criterion C₁₁: the relationships between the differential and through-currents are different in all three phases of the relay (*asymmetry checking* – an internal, three-phase symmetrical fault in a power transformer is practically impossible).

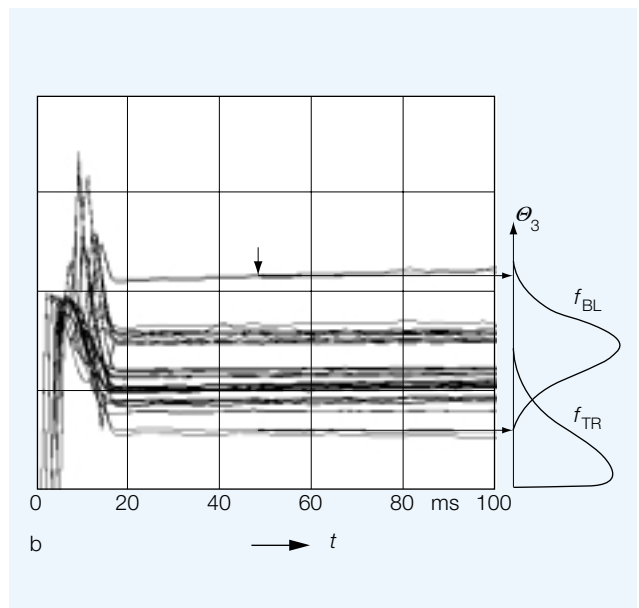
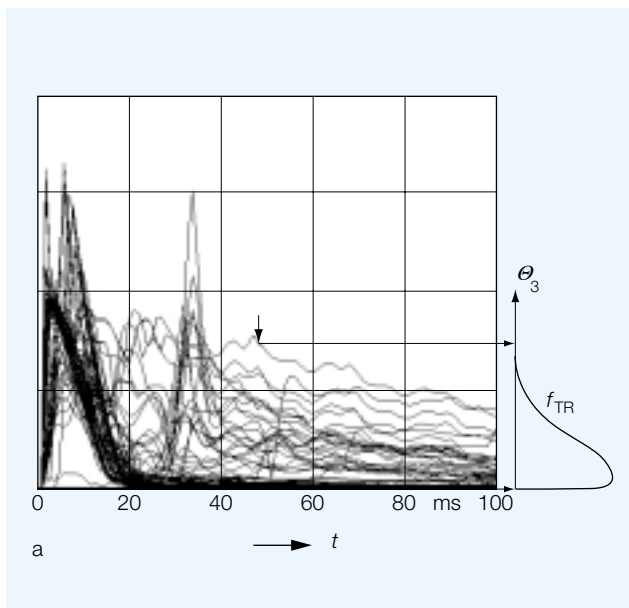
Criterion C₁₂: the differential current is greater than the highest expected current value caused by a near, major

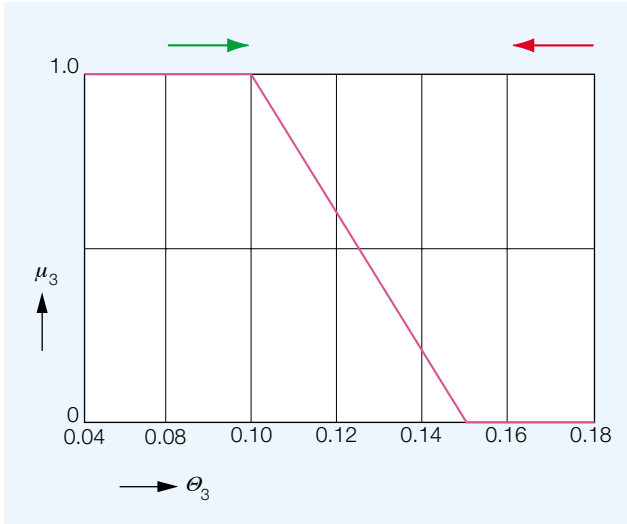
Distribution of the 2nd harmonic percentage in the differential current under internal fault (a) and inrush (b) conditions. The sample probability density functions for blocking (f_{BL}) and tripping (f_{TR}) are given for t = 50 ms.



t Time

θ₃ Criteria signal (2nd harmonic restraint)





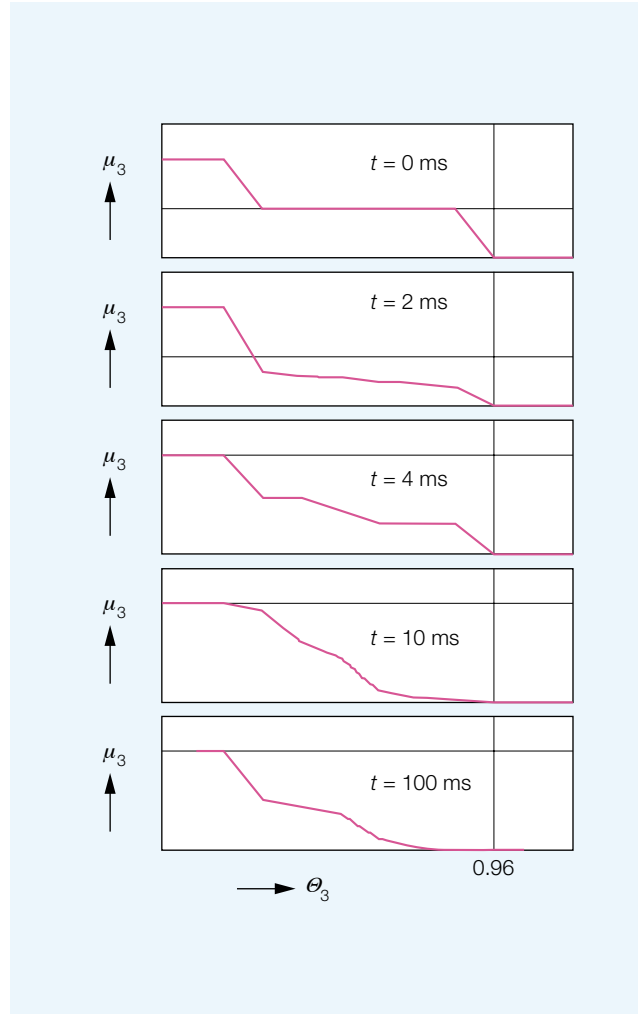
Arbitrary fuzzy setting μ_3 for the 2nd harmonic restraint (criterion C_3) **3**

μ_3 Fuzzy setting
 θ_3 Criteria signal (2nd harmonic restraint)

Green Certain non-inrush
 Red Certain inrush

Example of self-adjusted fuzzy setting for the 2nd harmonic restraint (criterion C_3). Screenshots of the time-varying setting, taken at $t = 0, 2, 4, 10$ and 100 ms after relay start-up. **4**

μ_3 Fuzzy setting
 θ_3 Criteria signal (2nd harmonic restraint)



external fault and the largest possible mismatch of the transformer and CT ratios.

Protective relay based on fuzzy logic

Measuring unit

The measuring unit **1** of the considered FLR for power transformers measures the current on both sides of the protected unit and also the terminal voltage (if the latest signal is not available, C_5 is ignored and recognition of overexcitation is based on C_4 and C_6 only).

The unit forms the differential and through-currents according to the

transformer winding connections, activates the relay, measures the required relaying signals, and forms the criteria signals $\theta_1 - \theta_{12}$. The measurements are based on Finite Impulse Response (FIR) full-cycle orthogonal filters, designed using the least square method, with perfect separation between the 1st, 2nd and 5th harmonics. 1 kHz is assumed as a sampling rate (20 samples per cycle).

Fuzzy settings

The criteria signals are next fed into the non-linear functions, called fuzzy settings. **2** and **3** explain the idea of a fuzzy setting: **2** shows time distributions of the ratio of the 2nd and 1st

harmonic amplitudes of the differential current (θ_3) for inrush conditions **2b** and internal faults **2a**. The figures are obtained by plotting the signal $I_{\Delta 2(n)} / I_{\Delta 1(n)}$ on the same plane for all the collected cases (for inrush in **2b** and for internal faults in **2a**). From comparison of the figures and observation of the overlapping region between the distributions, it is concluded that there is no perfect threshold for the signal θ_3 in terms of avoiding recognition errors. Increasing the threshold speeds up operation of the relay under internal fault conditions accompanied by CT saturation, but it may cause false tripping under inrush conditions. On the other hand, reducing the threshold improves relay stability, but at the same time delays operation

of the relay. The same uncertainty applies to all the criteria signals, especially when the decision has to be made fast [3–5].

To resolve the problem and model this uncertainty numerically, the idea of a fuzzy setting has been introduced [4, 5]. **3** shows an arbitrary fuzzy setting μ_3 for criterion C_3 . If the percentage of the 2nd harmonic (θ_3) is below 10%, the case is classified by the criterion C_3 as ‘certain non-inrush’ and the continuous logic signal μ_3 takes the value 1.0. If the signal θ_3 is above 15%, the inrush supposition is confirmed without any doubt, and the signal μ_3 equals 0.0. The doubtful region extends over the 10–15% range, where μ_3 changes from 1.0 (inrush excluded) to 0.0 (inrush confirmed). The signal μ_k may be understood as the level of permission for tripping provided by the criterion C_k .

As a result of this signal-setting comparison, the criteria signals $\theta_1 - \theta_{12}$ convert into the continuous logic signals $\mu_1 - \mu_{12}$.

Multi-criteria aggregation

If the situation is clear, the signals $\mu_1 - \mu_{12}$ reduce to boolean logic variables and equal either 0 or 1. Under unclear conditions, however, they may take values from the 0 – 1 interval, and thus give partial support to certain hypotheses. Moreover, the recognition provided by the different criteria may be contradictory. On top of this, the criteria differ in terms of the quality of their recognition; some are more, some less reliable. In order to resolve this and balance the decisions made by the criteria with the criteria powers, multi-criteria decision-making methods are recommended [4, 5].

For the cases under consideration, the weighting factors method is used [3]. The criteria C_1 , C_2 and C_3 , on recognizing inrush conditions, are aggregated by computing the average level

of ruling out of the inrush hypothesis ω_1 :

$$\omega_1 = w_1\mu_1 + w_2\mu_2 + w_3\mu_3, \quad (2)$$

$$w_1 + w_2 + w_3 = 1$$

w_k Weighting factor reflecting the recognition power of criterion C_k

Analogous computations are performed for ω_2 , ω_3 and ω_4 . Under ideal conditions it is observed that inrush causes $\omega_1 = 0$, overexcitation induces $\omega_2 = 0$, etc. And when an internal fault occurs: $\omega_1 = \omega_2 = \omega_3 = \omega_4 = 1$.

Decision-making

The relay should rule out all the non-internal fault hypotheses (a – d) prior to tripping. Consequently, signals $\omega_1 - \omega_4$ are aggregated into the overall tripping support (δ) by means of a continuous logic AND-operator [3]:

$$\delta = \min(\omega_1, \omega_2, \omega_3, \omega_4) \quad (3)$$

Tripping is initiated if δ is greater than the time-varying, even adaptable tripping threshold Δ :

$$Trip = (\delta \geq \Delta) \quad (4)$$

Thus, all the logical operations are performed in the fuzzy logic system and the necessary conversion to the boolean logic takes place once only at the output of the protection scheme.

Algorithms for self-adjustment of the relay

The following components of an FLR may be self-adjusting and set prior to installation [3]:

- Fuzzy settings, $\mu_1 - \mu_{12}$
- Criteria weighting factors, $w_1 - w_{12}$
- Tripping threshold, Δ

All three components can be either stationary or non-stationary (time-vary-

ing). The algorithms have been developed primarily for the non-stationary variants, but the methods can be easily re-constituted for the stationary versions.

The algorithms are based on probability density functions of the criteria signals under the operating conditions most relevant for a protected transformer. Such probabilistic diagrams have been found by means of a large number of simulations performed with ATP-EMTP [8].

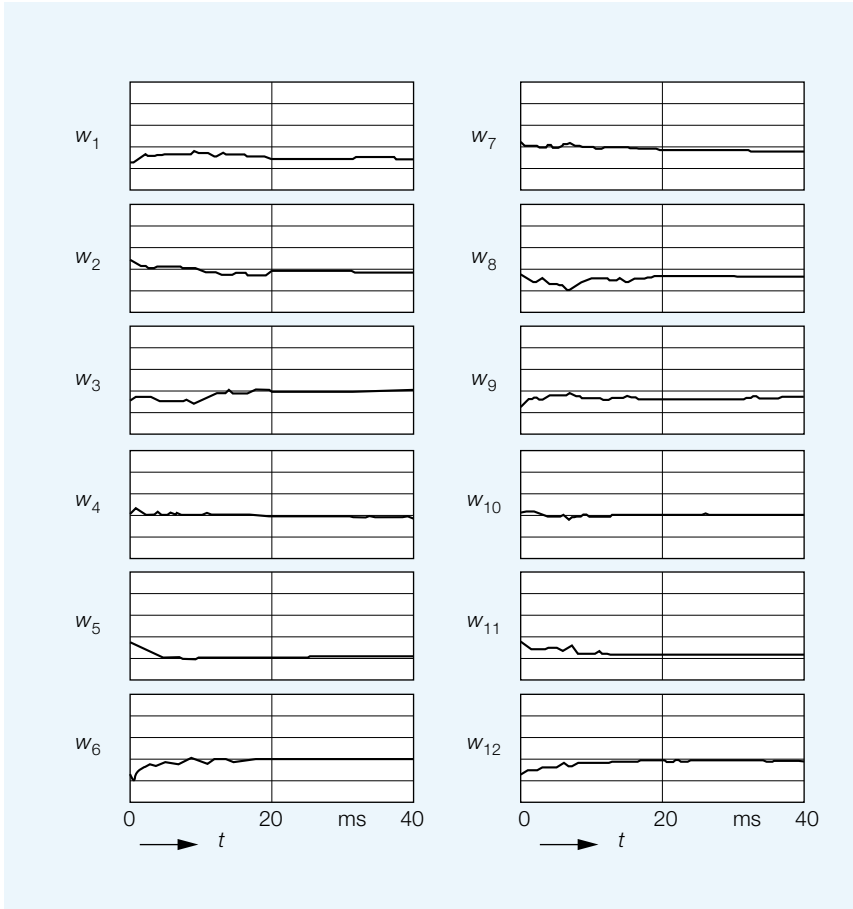
Test cases

A digital, ATP-based model of a three-phase, two-winding, Yd-connected, five-leg core type power transformer rated at 5.86 MW and 140/10.52 kV, provided the input for the FLR. The most important factors taken into account by the model [7] included: representation of both the saturation and hysteresis loop of a transformer iron core, the feasibility of input of a residual flux, representation of the main CTs in terms of their possible saturation, representation of the relay input circuits with relay CTs and anti-aliasing analog filters, and the feasibility of modelling turn-to-turn internal faults.

During the simulation, certain random variables were distributed uniformly to ensure the diversity of the studied cases. These variables included the residual magnetism, voltage angle at the beginning of the disturbance, fault location and resistance, number of short-circuited turns, type of fault, pre-fault transformer burden, CT saturation levels, mismatch of the transformer and CT ratios, and the power system configuration.

Self-adjustment of the fuzzy settings

Comparison of **2a** and **2b** shows where the distribution of the sample criteria sig-



Self-adjusted weighting factors for the protection criteria

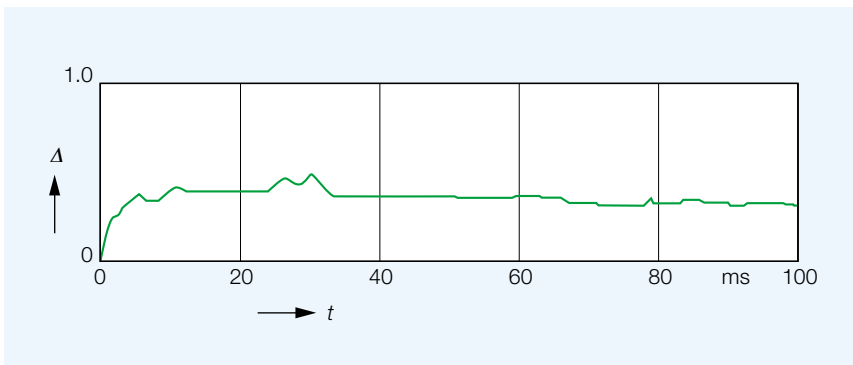
t Time
 w_{1-12} Weighting factors for criteria 1 – 12

nal (Θ_3) overlaps, this region being likely to cause a delay in relay operation or even failure of the relay to operate,

depending on the threshold established for this signal. This region also changes with time, and with it the ability of the cri-

Self-adjusted time-varying tripping threshold

t Time
 Δ Tripping threshold



terion C_3 to distinguish between inrush and internal fault patterns. Taking this into account by making the setting μ_3 time-varying as well as fuzzy further improves the quality of recognition of the criterion.

As shown in [3], the shape of a fuzzy setting may be found automatically by analyzing the simulation of a protected element prior to installation of the relay. This makes the relay self-setting and to some extent capable of learning, eg as in artificial neural network applications [6].

4 shows, as an example, the self-organized fuzzy setting μ_3 . It should be noted that some time after the beginning of a disturbance (relay start-up) the setting becomes less fuzzy to accommodate the fact that CTs change from the saturated state to the non-saturated state in the event of certain severe internal faults.

Self-adjustment of the weighting factors

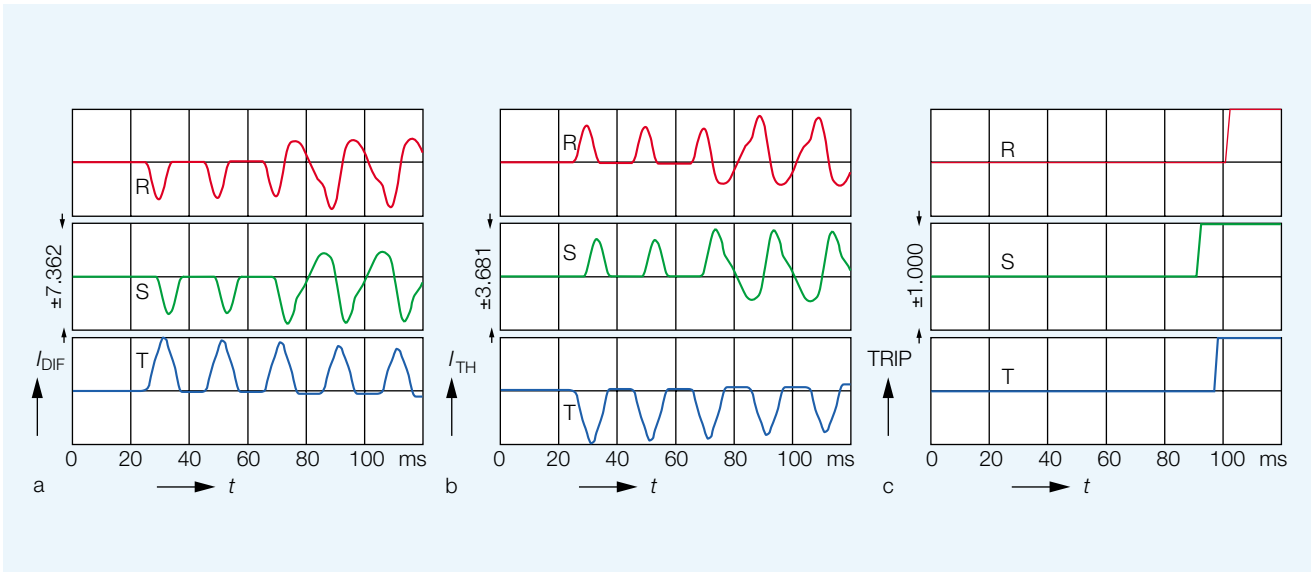
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By analyzing the behaviour of each criterion under both internal fault and other conditions it is possible to judge the strength (recognition power) of the criteria. These recognition powers are directly reflected by the values of the weighting factors 1. The proposed formal numerical algorithm can be found in [3].

6

From 5, which shows the self-adjusted weighting factors for the FLR, it can be concluded that:

- All the considered criteria reach their maximum level of recognition capability, as given by the weighting factors, in one cycle. The FLR is therefore effectively non-stationary, with respect to the weighting factors, only during the first cycle of operation.
- The overcurrent criterion (C_1 , C_4 , C_9 and C_{12}) is initially weak, but gains some 10ms after activation of the



Relay operation under sample turn-to-turn fault conditions during energization of the transformer 7

I_{DIF} Differential current
 I_{TH} Through-current

t Time
 TRIP Tripping command

relay due to the dynamics of the measuring unit.

- The 2nd harmonic restraint with respect to the inrush conditions (C_3) gains after one cycle. This change in recognition power is induced by transient overshoots of the ratio $I_{\Delta 2}/I_{\Delta 1}$ during internal faults **2a**, being reflected by delayed tripping. The different nature of the transients of the ratio $I_{\Delta 5}/I_{\Delta 1}$ makes the 5th harmonic restraint (C_6) much faster.
- The weighting factor w_7 of the sequence of events criterion (C_7) does not change with time as it operates very fast or not at all. A similar effect is observed for the criteria C_{10} and C_{11} .

Self-adjustment of the tripping threshold

The tripping threshold represents a boundary in the ‘universe’ of the tripping support δ between the tripping and blocking regions.

To overcome selectivity and stability constraints, the setting algorithm opti-

mizes the tripping threshold as follows [3]:

- To improve the selectivity of the relay, the threshold is set as low as possible.
- To ensure relay stability, the threshold is set as high as necessary.

The self-set tripping threshold for the FLR is shown in **6**.

The non-stationary tripping threshold $\Delta_{(n)}$ adjusted using the algorithm depends on the fuzzy tripping support δ , which in turn depends on criteria weighting factors and, consequently, on the fuzzy settings. Bearing the above relationship in mind, the sequence recommended for self-adjusting procedures is:

- 1 Fuzzy settings
- 2 Weighting factors
- 3 Tripping threshold

Testing the relay

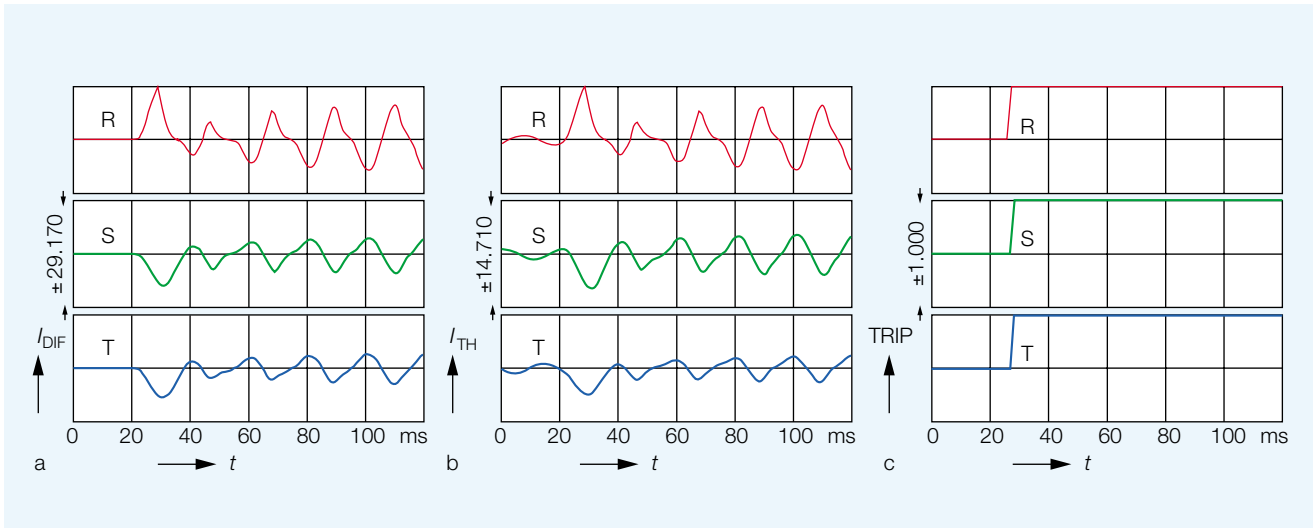
The selected examples demonstrate both the stability and the sensitivity of the fuzzy logic protective relay. **7** shows the differential and through-cur-

rents as well as the tripping signal for a turn-to-turn internal fault occurring 50 ms after the transformer is energized and involving 16% of the Y-side winding turns on column S. The relay is activated when energizing begins, but is blocked during inrush conditions. The tripping command is sent 16 ms after the fault inception.

The operation of the relay under internal fault conditions (R-to-S-to-ground fault at the terminals on the Δ -side) accompanied by CT saturation is shown in **8**. The relay is activated after 2 ms and trips 5 ms later.

Conclusions

The described multi-criteria, self-organizing fuzzy logic based protective relay for three-phase power transformers demonstrates important gains in sensitivity and selectivity compared with traditional approaches to protective relaying. The novel algorithms for off-line self-setting of the relay prior to installation are based on statistical information obtained by mass-simulation



Relay operation under sample internal fault conditions accompanied by CT saturation

8

I_{DIF} Differential current
 I_{TH} Through-current

t Time
 TRIP Tripping command

using an ATP package and allow a learning phase similar to that known from artificial neural network applications in power system protection schemes. The examples and results of relay testing demonstrate the high selectivity and sensitivity of the relay, which operates with an average tripping time of less than half a cycle. The robustness of the relay has also been confirmed.

References

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Authors' addresses

Dr. Murari M. Saha
 Birger Hillström
 ABB Network Partner AB
 S-721 71 Västerås
 Sweden
 Telefax: +46 21 14 6918
 Email:
 murari.saha@senet.mail.abb.com
 birger.hillstrom@senet.mail.abb.com

Dr. Bogdan Kasztenny
 Dr. Eugeniusz Rosolowski
 Technical University of Wrocław
 Wrocław, Poland
 Telefax: +48 71 320 3487