2012

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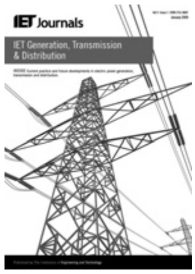
IET GENERATION TRANSMISSION & DISTRIBUTION, HERTFORD, v. 6, n. 10, pp. 1009-1018, OCT, 2012
http://www.producao.usp.br/handle/BDPI/36196

www.ietdl.org

Published in IET Generation, Transmission & Distribution
Received on 19th October 2011
Revised on 29th March 2012
doi: 10.1049/iet-gtd.2011.0711



ISSN 1751-8687

New approach for power transformer protection based on intelligent hybrid systems

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Abstract: A power transformer needs continuous monitoring and fast protection as it is a very expensive piece of equipment and an essential element in an electrical power system. The most common protection technique used is the percentage differential logic, which provides discrimination between an internal fault and different operating conditions. Unfortunately, there are some operating conditions of power transformers that can mislead the conventional protection affecting the power system stability negatively. This study proposes the development of a new algorithm to improve the protection performance by using fuzzy logic, artificial neural networks and genetic algorithms. An electrical power system was modelled using Alternative Transients Program software to obtain the operational conditions and fault situations needed to test the algorithm developed, as well as a commercial differential relay. Results show improved reliability, as well as a fast response of the proposed technique when compared with conventional ones.

1 Introduction

A power transformer is a very expensive electrical device, and its operation directly affects the performance of other equipment to which it is connected. Therefore it is necessary to use efficient protection schemes and monitoring systems in order to ensure its physical integrity, as well as a long operating lifetime [1]. Considering this, the most widely used technique to perform the protection function is the differential current logic, which allows discrimination between internal faults and other operating conditions [2].

Typically, a differential relay compares the output currents from a transformer's terminals to predetermined thresholds. When an internal fault occurs, the equipment is disconnected from the power supply. However, there are some situations that mislead this method, offering some limitations to its application. Among these situations, inrush due to energisation, as well as sympathetic inrush can be mentioned [3].

In order to prevent the malfunction of the relay, it is necessary to identify and distinguish between an inrush and a fault current. The literature shows that the most widely used technique to solve this problem is the harmonic restraint method. This approach is based on the fact that each phenomenon is characterised by a certain frequency spectrum, for example, the presence of the second harmonic for inrush current signals. However, there are some operating situations, such as sympathetic inrush [4], where the traditional technique fails and may affect the differential relay operation. This fact has encouraged researchers to improve sensitivity, precision, as well as efficiency of the differential protection applied to power transformers, using new techniques such as artificial neural networks (ANN), fuzzy systems (FS) and Park's power components [1, 5–9]. Concerning transformer protection facing current transformer (CT) saturation, many methods can be found in the literature for its mitigation, and the majority of the techniques utilise pattern recognition, derivative equations related to the CT, least error square method or simply the blockage of the protection function when saturation is detected [10–12].

This paper presents an algorithm for differential protection of power transformers based on intelligent systems. The proposed method consists of three main steps: data acquisition with CT saturation correction by ANNs (using Shannon's entropy), the estimation of the current harmonic components by genetic algorithms (GAs) and decision making by FS. In addition to the proposed algorithm, a complete electrical system was modelled using the Alternative Transients Program (ATP) software in order to generate the various operating and fault situations concerning power transformers. The proposed algorithm has shown excellent results facing inrush and sympathetic inrush, as well as a shorter operating times compared with conventional techniques available, especially in commercial relays.

2 Harmonic model of the current signal using GA

A signal can be defined as a function that carries information, usually about a state or a procedure of a physical system.

However, signals can be represented in several ways. Mathematically, a periodic signal can be suitably represented in terms of its fundamental frequency and harmonic components, expressed as a sum of sinusoidal waveforms referred to as the Fourier series. Each harmonic component has its own magnitude and phase angle, as well as a frequency that is a multiple integer of the fundamental system frequency [13]. Therefore the current into a transformer can be approximated as the sum of a zero-mean periodic part and an exponentially decaying DC offset, written as

$$x(t) = x_0 e^{-\lambda t} + \sum_{i=1}^{N} A_{c,i}\cos(i\omega_0 t) + A_{s,i}\sin(i\omega_0 t) \qquad (1)$$

where x_0 is the constant component of the signal; λ is its time constant; $A_{c,i}$ and $A_{s,i}$ are the cosine and sine amplitudes of ith harmonic, respectively; ω_0 is the fundamental frequency; i is the order of harmonic component and N is the number of harmonics used to represent $x(t)$.

However, although the signal is continuous in time, it must be sampled so that the computer algorithms can be used. Thus, the representation of the sampled signal is given by (2), where $e(t_k)$ is the error associated to each sampled instant of time (t_k) and m the total number of samples.

$$\begin{bmatrix} x(t_1) \\ x(t_2) \\ \vdots \\ x(t_m) \end{bmatrix} = [\boldsymbol{\Gamma}] \begin{bmatrix} x_0 \\ A_{c,1} \\ A_{s,1} \\ \vdots \\ A_{c,N} \\ A_{s,N} \end{bmatrix} + \begin{bmatrix} e(t_1) \\ e(t_2) \\ \vdots \\ e(t_m) \end{bmatrix} \qquad (2)$$

The sine and cosine matrix ($\boldsymbol{\Gamma}$) can be found in (3).

Usually in (2), the number of samples (m) is higher than the number of parameters to be estimated ($2N + 2$), which makes the solution of this system a complex task. This study proposes GAs in order to minimise the error vector ($\boldsymbol{e}[.]$) and thus provide an estimated signal that is closest to the one sampled. A GA is a search algorithm based on the mechanism of natural selection and genetics. A GA operates in a population of current approximations, the individuals, initially drawn in a random order, from which improvement is sought. Individuals are encoded as strings, the chromosomes, so that their values represent a possible solution for the optimisation problem [14]. The fitness function utilised is shown below [13]

$$f_a = \frac{1}{\sqrt{\sum_{k=1}^{m} e_k^2/m} + \Delta} \qquad (4)$$

where f_a is the fitness function, m is the number of samples in the signal and Δ is a very small positive constant (0.00001) aimed to avoid overflow problems.

Concerning the application of GA for the estimation of the parameters represented in (1), it should be mentioned that a complete model of the voltage and current signals was considered in [13, 15] in order to estimate the fundamental component, including the estimation of the harmonic components, as well as the decaying DC offset. It is well known that the decaying DC offset represented in (1) results in a phasor estimation error, depending on the algorithm used [16]. It must be pointed out that the GA presented a very good performance considering traditional methods such as the Discrete Fourier Transform (DFT) technique. The present paper made use of a real implementation of the GA with results compatible to the ones presented in [13, 15]. It is important to highlight that this improved result concerning the use of GAs will influence directly the transformer protection performance, as the FS will have more precise current component inputs. This application is one of the main scopes of this paper.

3 Proposed method

3.1 Relay flowchart

The proposed algorithm was implemented in the C++ programming language and it is shown in Fig. 1. It uses the IEEE standard common format for transient data exchange for the power system (COMTRADE) in order to acquire current and voltage signals from a transformer [17]. After acquiring the data and CT saturation correction, the signals are processed using GAs, and the differential and flux-

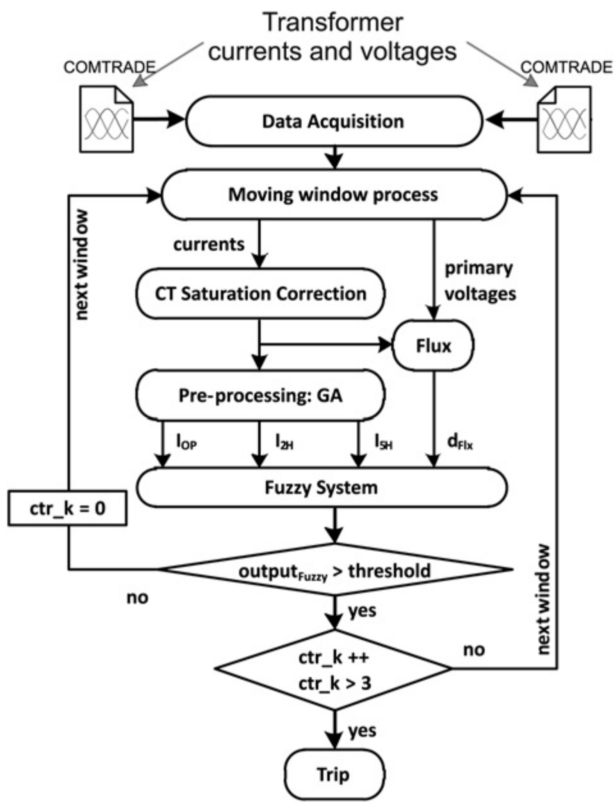

Fig. 1 *Basic relay algorithm*

$$[\boldsymbol{\Gamma}] = \begin{bmatrix} e^{-\lambda t_1} & \cos(\omega_0 t_1) & \sin(\omega_0 t_1) & \cdots & \cos(N\omega_0 t_1) & \sin(N\omega_0 t_1) \\ e^{-\lambda t_2} & \cos(\omega_0 t_2) & \sin(\omega_0 t_2) & \cdots & \cos(N\omega_0 t_2) & \sin(N\omega_0 t_2) \\ \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\ e^{-\lambda t_m} & \cos(\omega_0 t_m) & \sin(\omega_0 t_m) & \cdots & \cos(N\omega_0 t_m) & \sin(N\omega_0 t_m) \end{bmatrix} \qquad (3)$$

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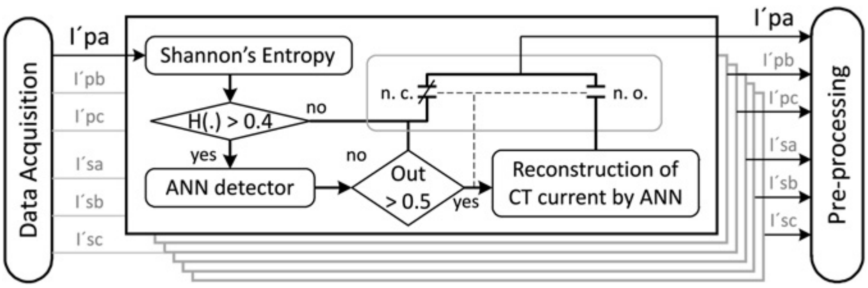

Fig. 2 *CT saturation correction flowchart*

restraint differential currents are calculated. These currents are the input of the FS. If the output of the FS is greater than the threshold value, 0.5, the control counter (ctr_k) is increased by 1. When this counter has exceeded 3, the relay sends a trip signal to the circuit breaker.

The following sections will describe each block individually.

3.2 Data acquisition

All practical stages in the data acquisition were taken into account, which allowed for a more realistic analysis of the results. The input current and voltage signals from the ATP software were characterised by a high sampling rate (9.6 kHz) to better represent the analog signals.

A second-order low-pass Butterworth filter with a cut-off frequency of 360 Hz was utilised. A sample rate of 960 Hz and an analog-to-digital converter (ADC) of 16 bits were also used. The low-pass filter was used to prevent aliasing and to ensure that the digital signal after ADC conversion represents the original signal.

In addition, three other blocks were added which include: the ratio correction, the phase compensation and the filtering of zero sequence currents [18].

The data acquisition was carried out in a moving window with 32 samples using one sample step. The whole data acquisition process should be executed in the time between two consecutive samples, taking into account the moving window process and the available time for processing.

3.3 CT saturation correction using ANN

ANN has been extensively used in the literature for pattern recognition, whose design was inspired by the functioning of the human brain and components thereof. Most neural networks need trainning whereby the weights of connections are ajusted on the basis of presented patterns [19].

This module of the general algorithm presented in Fig. 1 is intended to detect the CT saturation condition. If this condition is true, the module will proceed to the correction of the distorted waveforms by using ANN as well as the Shannon's entropy [12, 20]. Thus, instead of blocking the action of the algorithm and delaying the trip signal, as in a commercial equipment, the proposed technique will reconstruct the saturated current curve resulting in an improved performance of the transformer protection system. Fig. 2 illustrates the flowchart for the CT saturation correction.

The Shannon's entropy can be calculated by [20]

$$H(.) = -\sum_{i=0}^{m} p(x_i)\log_2 p(x_i) \qquad (5)$$

where $p(x_i)$ is the probability mass function of outcome (x_i) and m is the number of signal samples.

Table 1 shows the ANN configuration used to detect and correct the CT saturation, respectively. The inputs of the ANN are composed of the samples of the current, the sum of samples from the previous window and the Shannon's entropy, as shown in Fig. 3.

Fig. 4 shows the ANN output for an external fault with CT saturation together with the distorted signal, as well as the signal without saturation. It can be observed that the ANN output practically coincides with the signal without saturation, attesting the quality of the methodology used.

3.4 Pre-processing: genetic algorithm

After conditioning and correcting the CT saturation, the current signals are the inputs to the GA in order to extract the fundamental and harmonic components of both the primary and the secondary currents from the protected transformer, as explained in Section 2. It is important to note that these components may be used in the discrimination of the equipment's operating conditions, as each situation has a particular pattern [21]. Fig. 5 shows the flowchart for the phase A pre-processing stage.

Table 2 presents the parameters concerning the GA used for the proposed technique.

Table 1 Specification of the ANNs used in the CT saturation correction

	ANN detector	ANN corrector
topology	34-33-1	34-20-5-1
momentum	0.7	0.8
learning rate	0.1	0.01
activation function	sigmoid ($\beta = 1$)	sigmoid ($\beta = 1$)
training algorithm	backpropagation	backpropagation
type of ANN	multi-layer perceptron	multi-layer perceptron

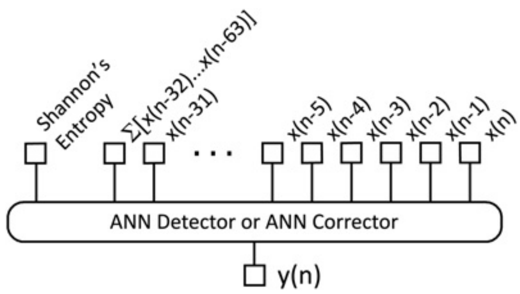

Fig. 3 *ANNs inputs*

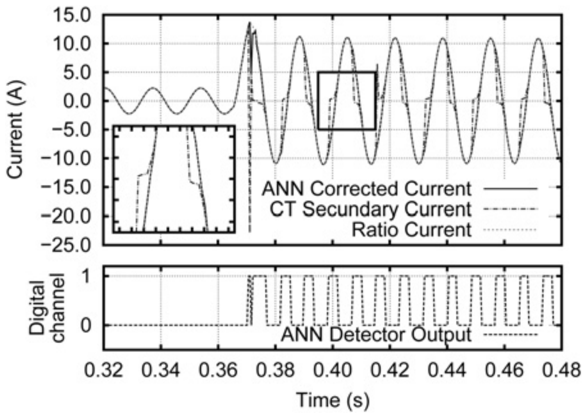

Fig. 4 *Current waveform corrected by ANNs application*

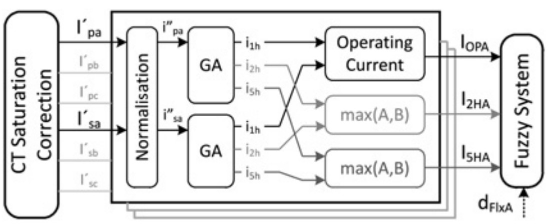

Fig. 5 *Pre-processing flowchart*

Table 2 Specification of the GA used for this approach

elitism operator	2 individuals
crossover rate	90%
crossover operator	arithmetic mean
mutation rate	5%
mutation operator	Gaussian ($\sigma = 0.05$)
population size	30 individuals
selection method	roulette wheel
stop criterion	15 000 generations
parameter's representation	real codification

It is important to emphasise that although the GA application involves a large computational effort, these models can be successfully used in real-time applications, as presented in [22, 23].

3.5 Design of the fuzzy system

A FS is a computing model that uses the approximate reasoning for qualitative information process of input data by linguistic knowledge [24]. The FS is used to deal with the input imprecisions without data loss during processing in order to determine the fault condition more precisely than conventional differential protection methods.

Some of the steps of fuzzy logic are:

3.5.1 Fuzzification: The fuzzification process consists of converting each crisp value into an equivalent corresponding linguistic term by associating a membership degree. This procedure provides that the uncertainty of the input relaying signals is quantified and all information contained is obtained without loss.

The FS applied to the proposed method uses four fuzzy inputs:

- i_{op}, i_{2h} and i_{5h}: where i_{op} ($i_{op} = i_d/i_{rt}$) is the operating current; i_d is the differential current ($i_d = |i_p + i_s|$); i_{rt} is the restraint current ($i_{rt} = 0.5\cdot|i_p - i_s|$); subscripts p and s represent the primary and secondary sides of power transformer; i_{2h} and i_{5h} are the largest second and fifth-harmonic components of the primary or secondary currents of the power transformer.

$$d_{Flx} = \frac{(\Delta t/2)(v_{p,k} - v_{p,k-1}) - L_p(i_{p,k} - i_{p,k-1})}{(i_{p,k} - i_{s,k}) - (i_{p,k-1} - i_{s,k-1})}$$

where d_{Flx} is the flux-restraint differential current; Δt is the sampling interval; i is the input current; v is the primary voltage; L_p is the leakage inductance of the primary winding and k is the number of the sample [25].

The fuzzy logic proposed uses fuzzyfication of the four input variables presented by two trapezoidal membership functions defined in the range of 0 to 1. These membership

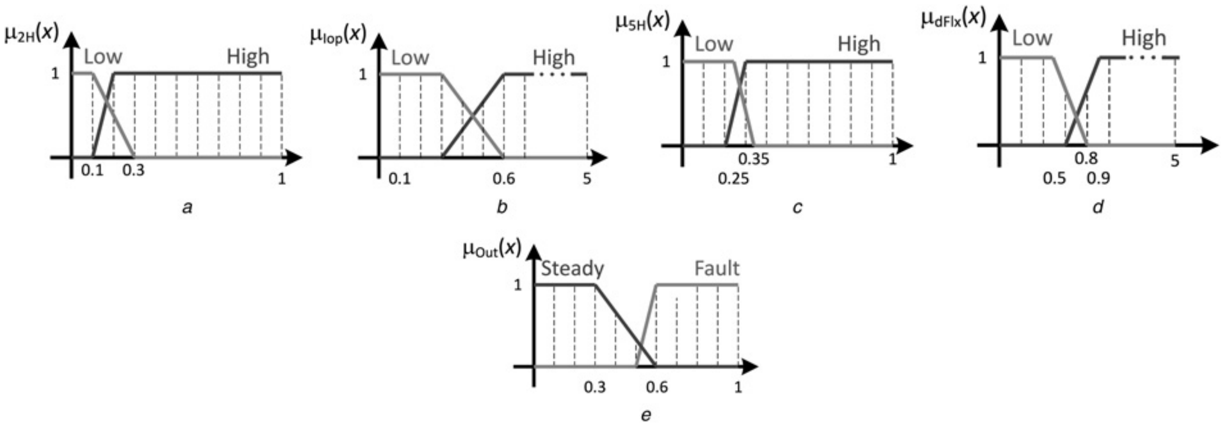

Fig. 6 *Fuzzy membership functions*

a Input fuzzy set 2 h
b Input fuzzy set I_{op}
c Input fuzzy set 5 h
d Input fuzzy set Flx
e Output fuzzy set

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doi: 10.1049/iet-gtd.2011.0711

Table 3 Summary of the fuzzy rules

Rule	i_{2h}	i_{5h}	i_{op}	d_{Flx}	Output
1	low	low	low	low	steady state
2	low	low	low	high	steady state
3	low	low	high	low	fault
4	low	low	high	high	fault
5	low	high	low	low	steady state
6	low	high	low	high	steady state
7	low	high	high	low	steady state
8	low	high	high	high	fault
9	high	low	low	low	steady state
10	high	low	low	high	steady state
11	high	low	high	low	steady state
12	high	low	high	high	fault
13	high	high	low	low	steady state
14	high	high	low	high	steady state
15	high	high	high	low	steady state
16	high	high	high	high	steady state

functions indicate that the value of the input variable is high or low, making it possible to check the status of the protected equipment, whether a fault or normal operation occurs. Fig. 6 shows the sets of input/output for the FS considered.

3.5.2 Inference method: Fuzzy inference is the process of formulating the mapping from a given input to an output. This is achieved by using an antecedent part of the fuzzy rule on his consequent. The proposed relay uses 16 rules to discriminate two operating conditions: steady state or internal faults. In order to perform a mathematical operation, the Mamdani method was chosen in this work [24]. Table 3 shows the rules used in the proposed algorithm.

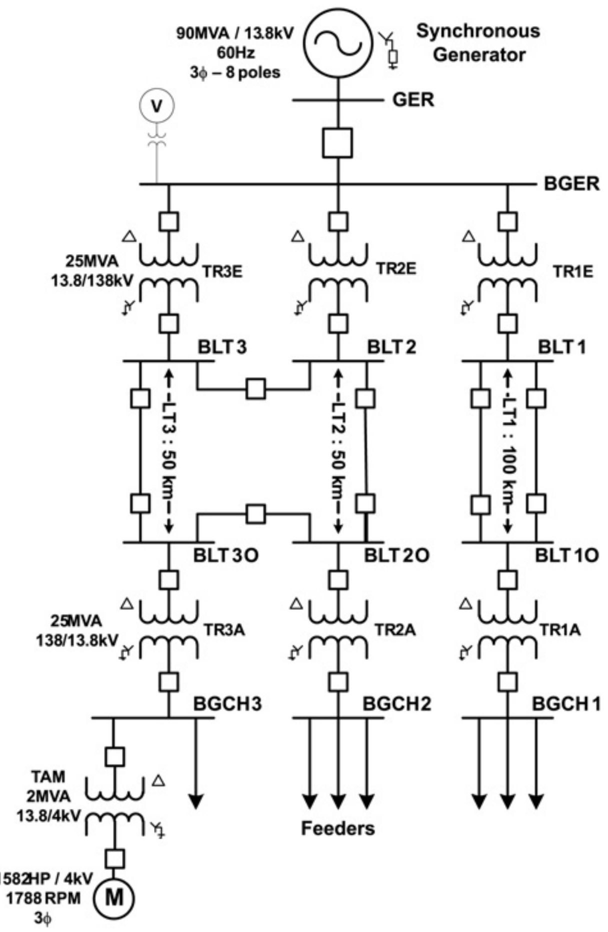

Fig. 7 *Power system representation using ATP software*

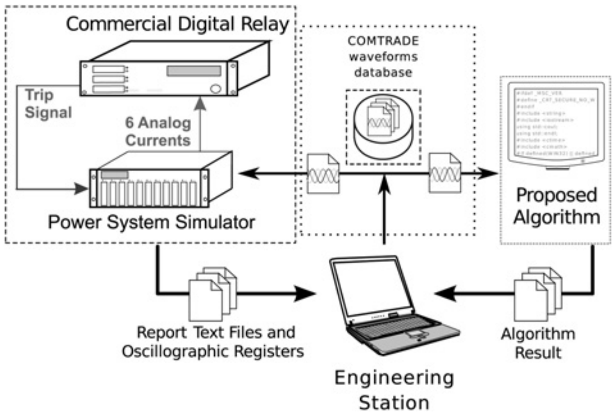

Fig. 8 *Laboratory set-up*

3.5.3 Defuzzification: The result of a fuzzy inference is a fuzzy output set. However, for control purposes a crisp value is necessary. The procedure to obtain this quantity is called defuzzification. The technique applied was a centroid given by (6) [24].

$$\text{output} = \frac{\sum_{j=0}^{N} y_j \mu_F(y_j)}{\sum_{j=0}^{N} \mu_F(y_j)} \tag{6}$$

where y_k is the value of each point on a domain of a final output fuzzy set and $\mu_F(y_k)$ is the membership value at each point.

4 Simulated electrical system

The electrical system was simulated using the ATP software. Fig. 7 shows the representation of the simulated power system, taking into account load switching and permanent faults in order to evaluate the differential technique proposed in this work.

The simulated power system consists of a 13.8 kV and a 90 MVA (60 Hz) synchronous generator, 13.8:138 kV/

Table 4 Adjustments for differential protection

Parameter	Description	Adjust (Unit)
CTR_p	current transform ratio primary side	400:1
CTR_s	current transform ratio secondary side	40:1
I_{pkp}	differential pick-up	0.3 (p.u.)
SLP_1	slope 1	25 (%)
SLP_2	slope 2	50 (%)
T_p	transition point between slopes	3.0 (p.u.)
I_{inst}	differential instantaneous element	8.0 (p.u.)
I_{bl}^{2h}	second harmonic threshold	15 (%)
I_{bl}^{5h}	fifth harmonic threshold	35 (%)
REF	restricted earth fault	off

138:13.8 kV and 25 MVA three-phase power transformers, transmission lines between 50 and 100 km in length and loads between 5 and 25 MVA with an 0.92 inductive power factor. Power transformers have a delta connection in the low-voltage winding and a wye connection in the high-voltage winding. The power transformers were modelled using ATP software (saturable transformer component) considering their saturation curves and sectionalised windings in order to study internal earth and phase-to-phase faults.

Still concerning Fig. 7, the CTs considering their saturation curves and capacitor voltage transformers, as well as the dynamic speed control system for hydraulic generation and automatic voltage control (AVR) were modelled. More information about the power system studied can be found in [7, 26, 27].

5 Laboratory set-up

The technique proposed in this work was simulated in a power system laboratory for an open-loop test. The laboratory set-up that was used can be seen in Fig. 8.

The main equipment used includes a power system simulator, a digital differential protective relay, a manageable switch and an IBM PC (an engineering station). In Fig. 8, it can be observed that the COMTRADE files were generated with the transformer operating situations. These files were fed both to the proposed system and to the power system simulator. The power system simulator provided data in an analog form to the commercial digital relay. Taking this into account, compatible systems were compared (proposed methodology and commercial relay) considering that both utilise the same current waveforms and both go through their own digitalisation process. A brief description of the digital relay parametrisation used in the tests and the power system simulator can be found as follows.

5.1 Power system simulator

A power system simulator was used to obtain the behaviour of the power system in the laboratory during the faulted conditions and other situations of interest. Some interesting features of the equipment that allowed to perform transient tests on differential digital relays are:

- capability to import waveforms in COMTRADE format;
- existence of six current channels;

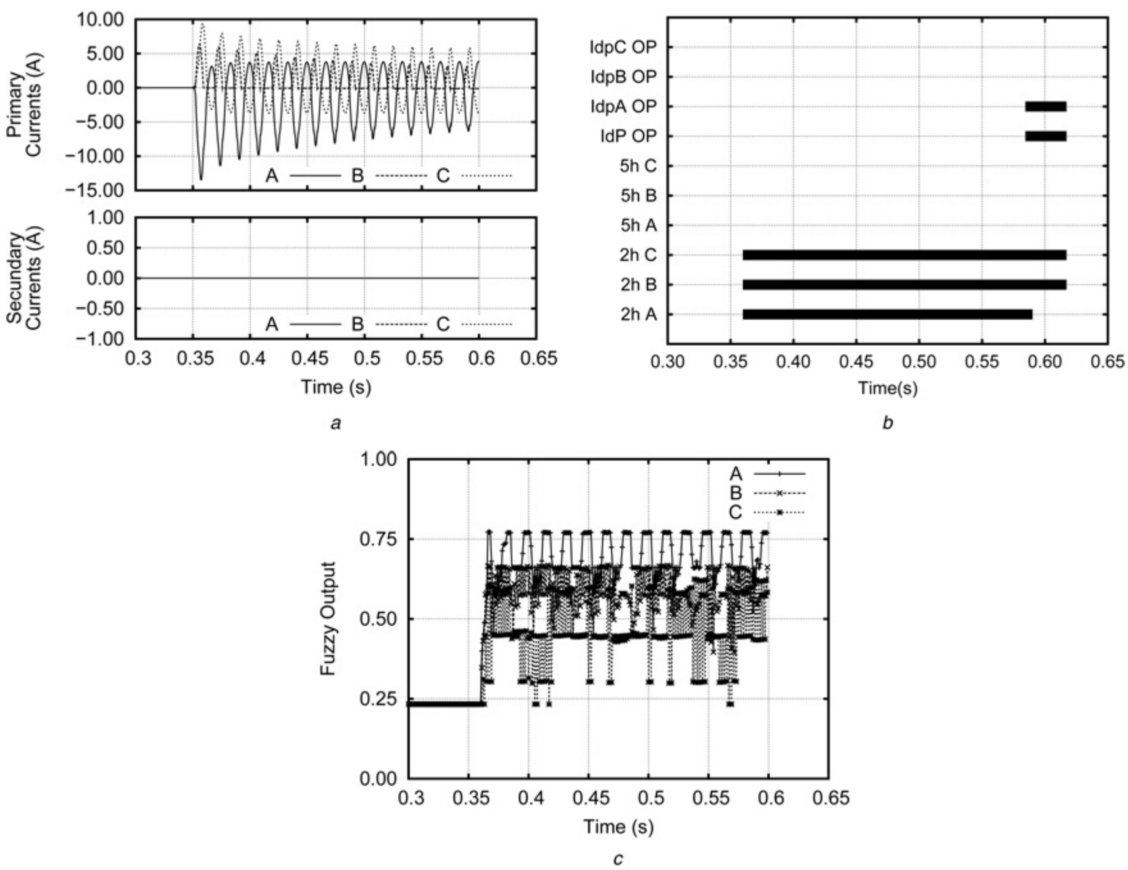

Fig. 9 *Energisation under a fault at 10% in the HV winding of phase A*

a Three-phase currents of the transformer
b Digital channels of the commercial relay ($t_{trip} = 234.60$ ms)
c Proposed relay output ($t_{trip} = 21.27$ ms)]

- capability to execute a set of tests automatically; and
- capability to record the relay operation time.

5.2 Commercial digital relay

A commercial digital relay for transformer protection was used to run the laboratory tests. The relay has a combination of single or dual slope percentage differential characteristics, overcurrent and restricted earth fault protection, as well as control, monitoring, automation and oscillographic record capabilities. Table 4 shows the adjustments used in the commercial differential relay.

It is important to emphasise that the commercial digital relay was used in the test scheme with the objective of comparing its response with the results presented by the proposed technique. The commercial protective relay utilised in this work uses a percentage restraint differential characteristic with a dual-slope and harmonic restraint. More details about the technique used by the commercial relay can be found in [28].

6 Results and discussion

The main purpose of this section is to present some results regarding the proposed algorithm comparing them to results using a commercial relay. Various different tests were simulated for distinct operating conditions of the power transformer in the system shown in Fig. 7. These simulations were converted into COMTRADE file format and the files were stored in a database having 690 cases of interest, including internal faults in both sides of the power transformer, sympathetic inrush, energisation, overexcitation, energisation under fault, interturn faults and CT saturation. This database was used to test and validate the proposed algorithm. However, for brevity only the 105 most relevant cases were used for comparison with the commercial relay. Each test set was repeated ten times and statistical equations were used to determine the operation times for the tested commercial digital relay (IEEE device function number 87 [29]) and the proposed technique.

6.1 Performance comparison between the commercial relay and the proposed technique

Fig. 9 presents an energisation case under an internal fault. This fault was in phase A at 10% of the high-voltage winding of TR2E transformer (Fig. 7). Fig. 9*a* shows the current waveforms in both sides of the protected transformer. In Fig. 9*b*, the output of commercial relay digital channels is presented. Finally, Fig. 9*c* presents the fuzzy logic output of the proposed technique.

From Fig. 9*b*, a delay of ∼210 ms in the digital channels from the oscillography of the commercial relay can be observed. This is caused by the blockage because of the harmonic restraint logic described earlier. However, this time delay does not occur when using the proposed fuzzy logic system, as shown in Fig. 9*c*. This system allowed for an efficient performance of the protection system in only 21.27 ms.

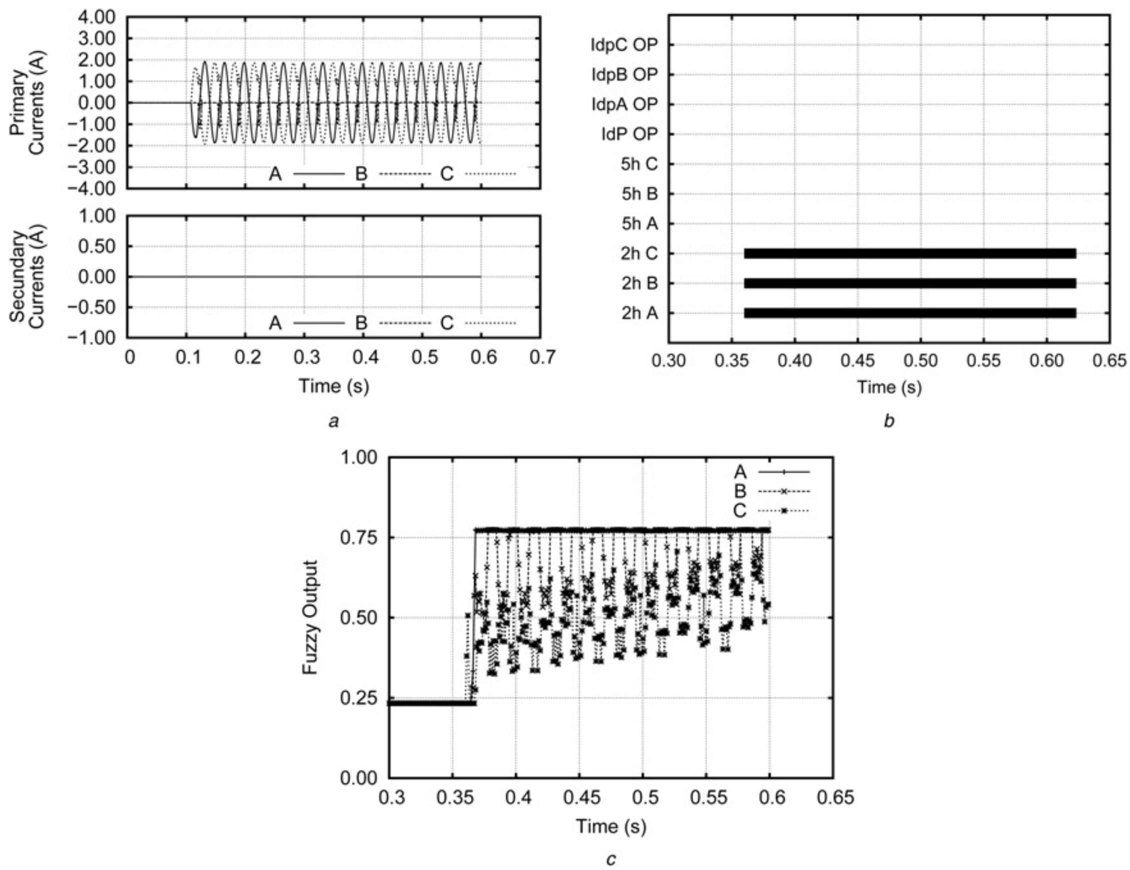

Fig. 10 *Energisation under a fault at 5% in the HV winding of phase A*

a Three-phase currents of the transformer
b Digital channels of the commercial relay
c Proposed relay output ($t_{trip} = 19.10$ ms)

doi: 10.1049/iet-gtd.2011.0711

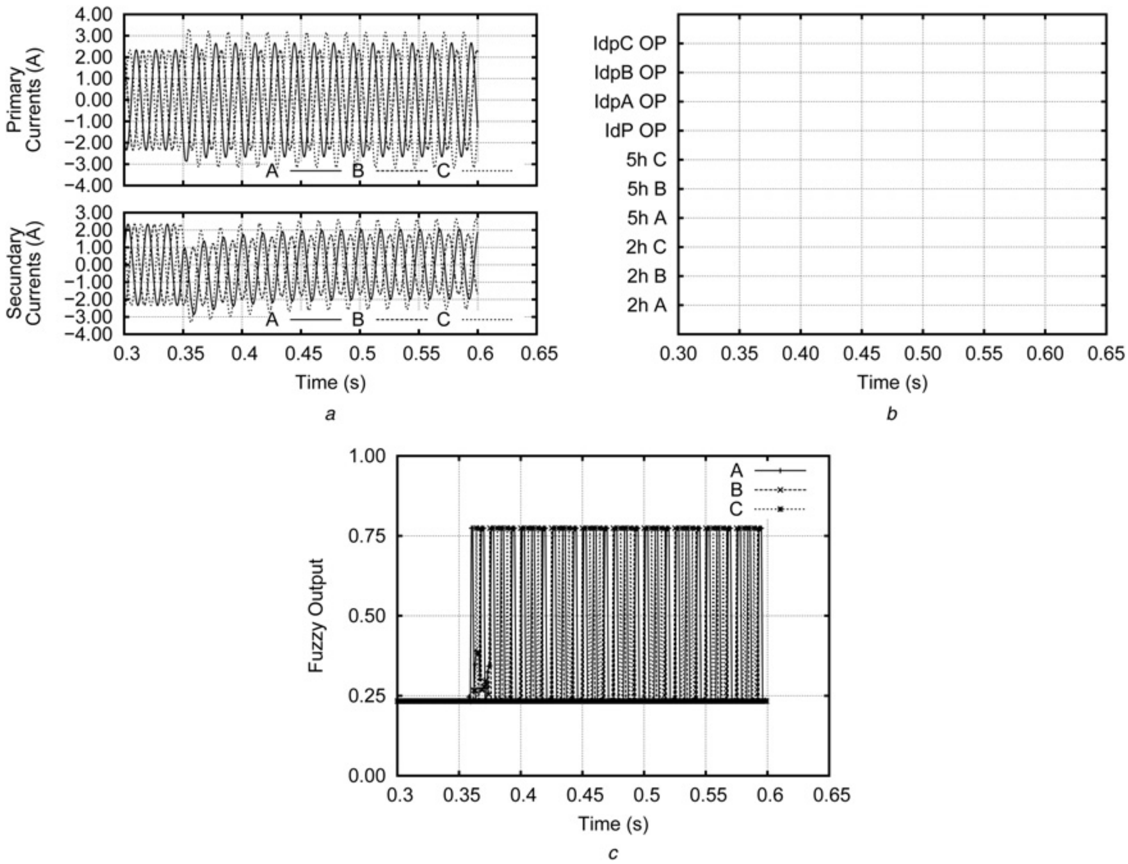

Fig. 11 *Internal fault at 5% of the secondary winding of phase A*

a Three-phase currents of the transformer
b Digital channels of the commercial relay
c Proposed relay output (t_{trip} = 19.10 ms)

It should be emphasised that for all situations evaluated concerning energisation with faults near the neutral, the fuzzy algorithm was faster than the commercial relay. This is true even considering the need for three consecutive responses large than 0.5 from the FS output.

Analogously to Fig. 9, Fig. 10 shows an energisation case under an internal fault in TR2E transformer (Fig. 7). The fault was in phase A at 5% of the high-voltage winding.

For the tests concerning energisation with fault, the commercial relay function (87 T) used was not able to detect faults inserted at 5% from the star winding neutral, as shown in Fig. 10*b*. In this scenario, the study highlights the robustness and accuracy of the proposed algorithm, as it detected the fault in ∼19 ms without the need of complementary functions, as shown in Fig. 10*c*.

Fig. 11 illustrates a case of the protected transformer with an internal fault at 5% of the star winding neutral in TR2E transformer (Fig. 7). It should be observed in Fig. 11*a* that there is only a small change in the behaviour in the faulty current of the transformer, if primary and secondary currents are compared, which implies in a great difficulty in detecting this situation. The commercial relay did not detect this fault (Fig. 11*b*) and the proposed technique once again worked properly for this case (Fig. 11*c*).

Fig. 12 illustrates the proposed algorithm behaviour and the commercial relay response for an external fault considering transformer TR2A with CT saturation. Although both methods perform appropriately for this fault condition, it should be observed that the commercial relay blocks the trip based on the harmonic content of the input signal, while the proposed technique reconstructs the waveforms through ANNs. It is important to note that although the ANN reconstruction significantly improves the incoming signals, there are still some distortions that will result in small oscillations in the output of the fuzzy logic, which do not result in bad performance for the proposed algorithm.

In order to show a global performance of the proposed technique compared with the commercial relay, some statistical tests were carried out for the 105 cases studied. Both methodologies were tested with different operation conditions such as energisation, energisation under fault, ground-fault, interturn fault, overexcitation, sympathetic inrush and CT saturation.

Tables 5 and 6 show the operating time (average – AvrgT, maximum – MaxT, minimum – MinT and standard deviation – DevT), as well as the percentage of errors for the proposed algorithm and the commercial relay for different operating conditions, respectively. The results show differences in operating times for various operating conditions, as well as differences on operating times of the commercial relays for the same test cases repeated many times. The main factor for the time variation in test cases is the different fault inception angles and the percentage of winding under a fault. The considered fault inception angle values were 0, 45 and 90. In this work, the windings were divided into 5, 10, 30, 50 and 80% from the neutral in the case of star winding and from the phase in the case of delta winding.

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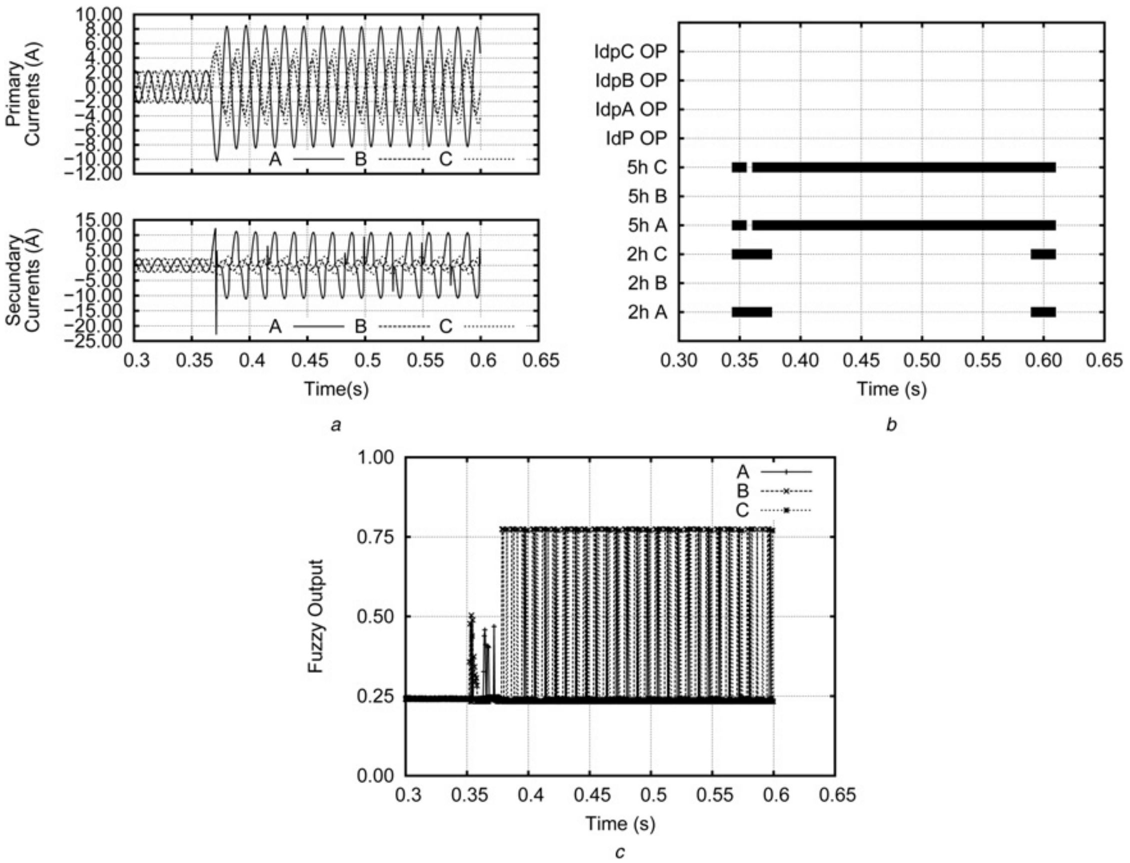

Fig. 12 *External fault with CT saturation*

a Three-phase currents of the transformer
b Digital channels of the commercial relay
c Proposed relay output (without 'trip')

Table 5 Statistical tests for the proposed algorithm

Description of operating condition	Proposed algorithm				
	AvrgT, ms	MaxT, ms	MinT, ms	DevT, ms	Error, %
energisation	–	–	–	–	0
energy under fault	18.57	21.87	15.49	1.46	0
ground-fault	13.57	25.66	7.43	4.81	0
interturn fault	12.12	18.04	8.35	2.44	0
overexcitation	–	–	–	–	0
sympathetic inrush	–	–	–	–	0
CT saturation	–	–	–	–	0

Table 6 Statistical tests for the commercial relay

Description of operating condition	Relay 87 T A				
	AvrgT, ms	MaxT, ms	MinT, ms	DevT, ms	Error, %
energisation	–	–	–	–	0
energy under fault	42.08	240.70	21.50	49.75	20
ground-fault	24.34	27.00	22.00	1.34	20
interturn fault	24.08	26.80	21.30	1.33	0
overexcitation	–	–	–	–	0
sympathetic inrush	–	–	–	–	0
CT saturation	–	–	–	–	0

It is important to note that errors relating to the commercial equipment are associated to faults near to the end of the winding, that is, less than 10% of the star winding. As presented, it is observed that for the situations of energisation, sympathetic inrush, CT saturation and overexcitation, both the commercial relay and the proposed technique presented feasible responses, but the proposed technique presented faster operating times.

7 Conclusions

This work presented an alternative technique for digital differential protection of power transformers using intelligent systems. An ANN was utilised to reconstruct saturated current signals and a GA was used to estimate the fundamental component and harmonics. A set of inference rules and subroutines based on fuzzy logic were developed in C++ language in order to identify internal faults and to discriminate them from other operating situations.

After analysing and comparing the results, the following advantages of the proposed algorithm could be observed:

1. Improved estimation of fundamental and harmonic components by the use of genetic algorithms.
2. Reconstructing of the input signal due to CT saturation allows proper protection functioning without the need of blocking.

Regarding the FS implementation, some comments should be made:

1. Decision making is more robust and reliable. The proposed algorithm worked properly even in situations of misoperation of the commercial equipment.
2. The output speed of the proposed algorithm was faster and showed to be more stable if compared to the commercial relay.
3. The developed algorithm based on FS can be applied to different situations and equipment as the inference rules and the inputs for fuzzyfication are flexible.
4. The trip decision was based on a simple comparison reducing the action of opening the breaker to the Boolean logic.
5. The algorithm developed has shown some robustness to failure of restraints because several variables are analysed simultaneously for decision making.
6. The proposed algorithm is straightforward, its configuration is unique, requiring no additional adjustments and knowledge of the other functions as in the case of the 87 commercial relay.

8 Acknowledgments

The authors acknowledge FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for the financial support, as well as the Department of Electrical and Computer Engineering, Engineering School of São Carlos, University of São Paulo, Brazil for research facilities provided to conduct this research project.

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doi: 10.1049/iet-gtd.2011.0711