Development of a Methodology for Evaluating the Reliability of Transformer Differential Protection Function Based on Monte Carlo Method

J. R. M. S. Souza, C. S. Pereira Filho, A. R. De Conti

Abstract-- **The aim of this paper is to present a time domain methodology to support the setting of transformer differential protective relays. This methodology, which is implemented in Scilab and ATP (Alternative Transients Program), uses concepts related to reliability theory and to Monte Carlo methods. Four different types of events were considered to illustrate the model application, namely transformer energization, external faults, internal bushings faults, and turn-to-ground faults. It is shown that the crossblocking technique leads to the highest success rate of the differential protection of a three-phase 41 MVA 138/34.5/13.8 kV power transformer during energization, compared with the harmonic restraint and independent harmonic blocking techniques. The sensitivity of the relay adjustments to the harmonic reference settings is also discussed. For the simulation of turn-to-ground faults, the obtained results suggest that the percentage restraint differential technique is not sufficiently accurate for transformer protection. On the other hand, a 100% reliability was obtained for the tests with external and internal bushing faults. The implemented relay model was validated through comparisons with data obtained from the operation of an actual relay in the laboratory. This suggests that the proposed methodology could be a useful tool for setting the transformer differential protection.**

Keywords: **Transformer, differential protection, time domain analysis, reliability, Monte Carlo Method.**

I. Introduction

There are several functions available in digital protective relays that are related to transient phenomena. Examples of this are schemes available in transformer differential protective relays to detect inrush currents, overexcitation, and current transformer saturation. In spite of this, the setting of transformer differential protective relays is often based on frequency domain studies, such as fault and power flow analysis [1]. Functions related to electromagnetic transients are usually set based on either manufacturer recommendations, generic studies made in the past, or staff experience. Although consolidated, this kind of procedure is limited in the sense that it does not take into account particularities that in some cases may compromise the protection system performance.

In this paper, a new time domain methodology is proposed to support the setting of transformer differential protective relays. In this methodology, which is implemented in the Scilab-ATP environment, concepts related to Reliability Theory and to Monte Carlo methods are used to identify the effectiveness of the differential protection of power transformers. To test the proposed methodology, several cases related to the following types of events were simulated: transformer energization, external faults, internal bushings faults, and turn-to-ground faults. The validity of the implemented model was then verified by means of comparisons with measurements performed with an actual relay.

This paper is organized as follows. Section II presents the basic concepts related to transformer differential protection and inrush current detection. Section III discusses the concept of reliability of the protection function, whose evaluation is the aim of this study. Section IV describes the proposed methodology, presenting both the modeling of the system components and the formulation of the Monte Carlo method. Section V presents results of application of this methodology to a series of events related to a 41 MVA three-winding transformer. Section VI illustrates the relay model validity by comparing the obtained results with the performance of an actual relay. Finally, Section VII presents the conclusions.

II. Transformer Differential Protection

A. Basic Concepts

Differential protection is one of the most popular techniques used for transformer protection because of its simplicity and efficiency. It is based on Kirchhoff's law, which enunciates that the sum of all currents flowing into a node is equal to zero. In other words, the current entering a device must be equal to the current leaving this device unless an internal fault occurs [1].

In a device with n branches, a differential current I_{diff} can be defined as in (1), where I_j is the current flowing through branch j. This differential current is also called operation current [2-4].

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$$I_{diff} = \frac{\left|\sum_{j=1}^{n} I_j\right|}{n} \quad (1)$$

When the protected device is a power transformer, the transformation ratio and the angular displacement must be compensated before (1) is calculated by the relay. The transformation ratio can be compensated by changing the current transformers ratio and/or by changing internal tap settings [15]. Angular displacement can be compensated by current transformer conections or by internal settings such as compensation matrices (only in digital relays) [4]. However, it is usually impossible to compensate for all sources of errors. Some conditions, such as current transformer errors and power transformer tap changes may produce a false differential current. To prevent misoperation, the differential current has to be compared with another current which is proportional to the current flowing through the power transformer. This current is called restraint current [2-4].

Each relay manufacturer proposes the use of a different equation to calculate the restraint current I_{rest}. Some examples are as follows.

$$I_{rest} = \frac{\sum_{j=1}^{n} \left|I_j\right|}{n} \quad [4] \quad (2)$$

$$I_{rest} = \sum_{j=1}^{n} \left|I_j\right| \quad [2] \quad (3)$$

$$I_{rest} = \max\left(\left|I_j\right|\right) \quad [3] \quad (4)$$

Differential and restraint currents define an operation characteristic such as that shown in Fig. 1. In this particular case, the protection scheme is called percentage restraint differential.

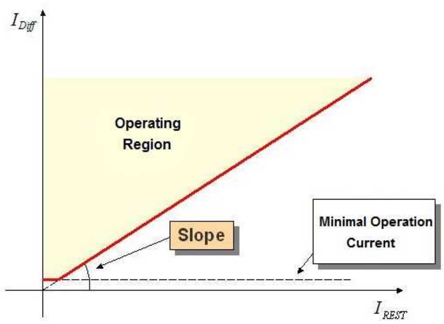


Fig. 1. Percentage restraint differential characteristic

Despite the combined use of I_{diff} and I_{rest}, some transient phenomena can lead to false differential currents and the consequent undesired operation of the protective scheme. One of the most frequent examples of this are inrush currents during transformer energization. It is therefore required that differential protection relays use some technique to detect inrush currents and prevent misoperations. Some of these techniques are described as follows.

B. *Inrush Current Detection Techniques*

Inrush currents are created during transformer energization because of the non-linearity of the transformer core [15]. Such currents present a rich harmonic content, which can be used for detecting their occurrence and avoiding the misoperation of the differential relays designed to protect the power transformer. In general, the third harmonic is not used because it can be filtered out by delta-connected windings. As a consequence, the second and fourth harmonics are usually preferred for inrush current detection [2-4].

Several different methods exist for detection of inrush currents. One possibility is the use of the so-called harmonic blocking technique. In this technique, the ratio of second and/or fourth harmonic in the differential current of each phase is evaluated. If this ratio exceeds a preset value, a blocking signal is generated. So, the relay takes the decision to trip or not to trip by combining the block signals of each phase with the operation signal generated by the differential protection function of each phase. There are several ways to do this combination:

- Independent blocking – the blocking signal of each phase inhibits the operation signal of this phase only [2-4].
- Crossblocking – the blocking signal of any phase inhibits all three operation units [2-4].
- 2-out-of-3 blocking – if two blocking signals are generated, all three operation units are inhibited [3]
- Average blocking – only one block signal is generated based on the average of the harmonic content of all three phases [3].

Another technique used to detect inrush currents is the harmonic restraint [4]. In this technique, the percentage restraint differential characteristic is changed according with the second and/or fourth harmonic content by the addition of a constant c, such as shown in equation (5) below.

$$I_{diff} \geq SLP \cdot I_{rest} + c \quad (5)$$

The constant c depends on the second and/or fourth harmonic content. So, when the protected transformer is energized, the percentage restraint differential characteristic is offset, preventing the relay misoperation.

All foregoing techniques are used in this paper for evaluating the performance of the differential protection of a power transformer.

III. Reliability of Relay Settings

Reliability R of a device (or a system) is the probability of this device (or this system) to perform its intended function for a specified time under certain preset conditions [5]. The complementary of the reliability R is the failure distribution function F. Equation (6) shows the relationship between these two quantities.

$$R(t) = 1 - F(t) \quad (6)$$

The failure distribution function F expresses the total number of failures expected in an initial population of devices in a certain time. Another quantity called failure rate, λ, expresses the frequency of occurrence of these failures. The complementary of λ is the success rate P. Equation (7) shows the relationship between these two quantities.

$$P(t) = 1 - \lambda(t) \quad (7)$$

The failure rate is a function of time and its most famous time behavior is given by the bathtub curve shown in Fig. 2-A. However, there are other kinds of failure curves as shown in Figs. 2-B to 2-F [6].

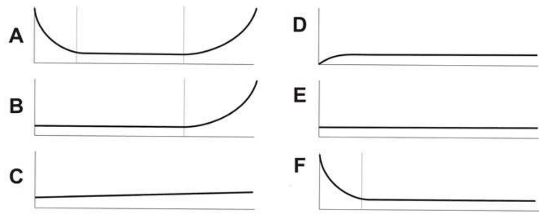


Fig. 2. Different kinds of failure rate curves [6].

The initial part of the bathtub curve shown in Fig. 2-A is called "Infant Mortality". It can be controlled by a procedure called "Burn-in". In this procedure, all devices are turned on and remain in operation at the factory during a certain time. So, all failures that are supposed to occur in the beginning of the device's lifetime will occur before this device goes to the final user.

The final part of the bathtub curve is related to the wear out failures. It can be controlled by the definition of the expected lifetime of the device. So, curves B, E and F are particular cases of the original bathtub curve A.

The aim of this paper is to evaluate the reliability of the transformer differential protection function during certain conditions. This consists basically in evaluating a software reliability. In this case, the commissioning tests may be considered as a "Burn-in" procedure and the "Infant Mortality" can be neglected. Since the lifetime of the differential function is related to the lifetime of its settings, and considering that no significant changes will occur in the system during the lifetime of the relay, such settings will end up being valid during a long time. In this case, the wear-out part of the bathtub can be neglected too. As a consequence, the failure rate will follow curve E and can be considered constant. If λ is constant, then the reliability can be calculated according to (8) [5].

$$R(t) = e^{-\lambda \cdot t} \quad (8)$$

IV. Developments

In this study, the differential protection of a power transformer is tested using the Monte Carlo method and concepts of reliability. For this, a software was written in Scilab [7] to implement a differential protection relay for time domain transient analyses. This software is also responsible for preparing input data cases for systematic simulation in ATP, and for reading and analyzing the results obtained after each simulation. Details of the implemented models are given in Section IV-A. A description of the Monte Carlo method used in the simulations is given in Section IV-B.

A. Modeling of system components

1) System Equivalent

The system equivalent seen from the busbar at which the transformer protection is analyzed was modeled with a balanced three-phase voltage source behind an RL coupled element represented in symmetrical components. The values of the positive and zero sequence resistance and reactance used in this study (see Table I) were obtained using the short-circuit analysis software ANAFAS [8], which contains a complete and accurate description of entire Brazilian power system.

TABLE I – SYSTEM EQUIVALENT

	R(pu)	X(pu)
Positive Sequence	2.6288	9.3253
Zero Sequence	6.5806	20.648

2) Power transformer

The power transformer whose differential protection is evaluated in this study is used at the high voltage distribution system of COPEL, which is the major power utility company operating in the state of Paraná, south of Brazil. It is a three-phase, 41 MVA, 138/34.5/13.8 kV power transformer, supplied from the 138-kV side, which feeds distribution networks of 34.5 kV and 13.8 kV. Since its winding configuration is Yg-yg-Δ, zig-zag grounding transformers are installed at the low voltage busbar to give a reference to ground protective relays installed at this side.

The power transformer was modeled following the same principles used in the hybrid model available in ATP [9]. However, the following simplifications and/or improvements were performed:

- Since the studied phenomena usually do not contain high-frequency components, capacitances and the frequency dependence of the winding resistance were neglected.
- The full coupling matrix [A] was used instead of the simplified matrix to take into account the difference between zero sequence and positive sequence parameters. The importance of this assumption is illustrated in Table II, which shows a comparison between current values obtained for a phase-to-ground fault at the primary winding bushing using a traditional frequency domain short-circuit analysis program (ANAFAS [8]) and ATP using both types of coupling matrix (full and simplified). Table II shows that results obtained when the full coupling matrix is used are closer to that obtained by ANAFAS.

TABLE II
CURRENTS CONTRIBUTIONS AT PRIMARY WINDING DURING A PHASE TO GROUND FAULT

Phase	ANAFAS	ATP (Simplified [A])		ATP (full [A])	
	Currents (A)	Currents (A)	Error (%)	Currents (A)	Error (%)
A	679.1	420.6	38.07	678.6	0.07
B	679.1	420.6	38.07	678.5	0.09
C	679.1	421.5	37.93	679.0	0.01

- To simulate turn-to-ground faults, the order of the coupling matrix [A] was increased by splitting the faulted winding in two.
- To extrapolate the excitation curve, a fitting to the modified Forlich equation was done, such as in the hybrid model [9]. However, to simplify the parameter estimation process, the empty-space inductance was neglected and the core was represented as a triplex one. As a consequence, the modified Forlich equation was written as shown in (9). Using the λ-i points that define the excitation curve of the transformer, it is possible to write the overdetermined system of equations (10). The parameters a, b and c in (9) and (10) can then be determined in a least squares sense using the pseudoinverse method [11] as (11).

$$\frac{1}{\lambda} = \frac{a + b\cdot|i| + c\cdot\sqrt{i}}{i} = a\cdot i^{-1} + b + c\cdot i^{-1/2} \quad (9)$$

$$\begin{bmatrix} \lambda_1^{-1} \\ \lambda_2^{-1} \\ \vdots \\ \lambda_n^{-1} \end{bmatrix} = \begin{bmatrix} i_1^{-1} & 1 & i_1^{-1/2} \\ i_2^{-1} & 1 & i_2^{-1/2} \\ \vdots & \vdots & \vdots \\ i_n^{-1} & 1 & i_n^{-1/2} \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix} \Rightarrow \bar{y} = \tilde{X}\cdot\bar{\theta} \quad (10)$$

$$\bar{\theta} = [(\tilde{X}^T\cdot\tilde{X})^{-1}\cdot\tilde{X}^T]\cdot\bar{y} = \tilde{P}\cdot\bar{y} \quad (11)$$

- The magnetization branch was modeled using the element 96 available in ATP [10]. To evaluate the effect of hysteresis, the Hysteresis ATP routine was used.

The parameters of the transformer model are listed in Table III. Details of the excitation curve are listed in Table IV.

To verify the transformer model, a comparison was made between inrush currents measured during the energization of the power transformer evaluated in this study and currents calculated with its model. The results are shown in Fig. 3. It must be noted that the simulated case is not identical to the condition in which the measurements were performed because of the difficulty of evaluating both the circuit breaker close time and the residual flux of each phase. However, the magnitude and shape of the obtained currents are in good agreement with measured data. This suggests that the simplifications adopted in the transformer model seem reasonable.

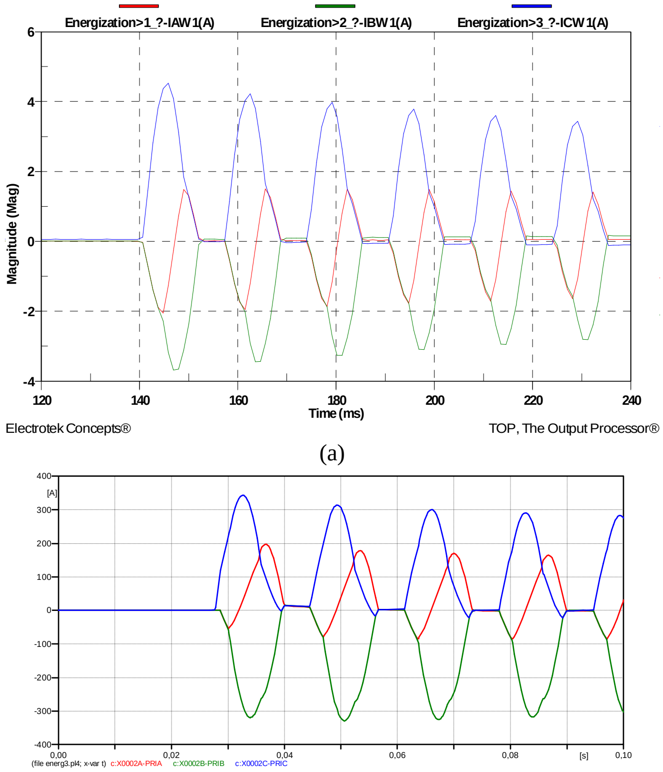
TABLE III – PARAMETERS OF THE MODELED TRANSFORMER

	Primary	Secondary	Tertiary
V (kV)	138	34.5	13.8
S (MVA)	41	41	41
Conection	Yg	Yg	D
R (pu) *	0.0065	0.0046	0.0064
X1 (pu) *	0.2662	-0.0236	0.1731
X0 (pu) *	0.1336	-0.0023	0.0910
Phase Shift (°)	-	0	30
Core loss (W)		21750	

(*)Power base = 100 MVA

TABLE IV – EXCITATION CURVE

V(kV)	12.46	13.88	14.52	15.57
I(A)	1.04	1.2	2.17	7.46



(b)

Fig. 3. Comparison between oscillographic records obtained (a) during a real transformer energization (currents in secondary values for a CT ratio of 600-5 A) and (b) through simulation using the proposed transformer model.

It is important to note that the aim of this study is to develop a methodology to evaluate the reliability of the transformer differential protection function. If necessary, the transformer model can be improved for future studies.

3) *Zig-zag Grounding Transformers*

The zig-zag grounding transformers used to provide a ground reference to the low-voltage side of the simulated transformer were modeled as a RL coupled element in symmetrical components. The parameters are listed in Table V. The positive sequence resistance and reactance were set with a very large value (10^6). However, the zero sequence resistance and reactance were set according COPEL specifications.

TABLE V – PARAMETERS OF THE ZIG-ZAG TRANSFORMERS

	R(ohms)	X(ohms)
Positive Sequence	10^6	10^6
Zero Sequence	0.20	6.78

4) Differential Protection Relay

The digital protection relay implemented in Scilab is based on a real digital relay that can use either harmonic restraint, independent blocking or crossblocking of second and fourth harmonic for preventing undesired operation during transformer energization [4]. The implemented model reads output currents calculated in ATP using an integration step of 100 µs and performs the phasor estimation at a sample rate of 64 points per 60 Hz cycle. So, the first procedure executed by the relay model function is the interpolation of the current input signal.

After interpolation, a low-pass filtering is done with a third order Butterworth filter. The cutoff frequency was set to 300 Hz because the relay model requires the fourth harmonic component (240 Hz) of the signals. The filtered signal is sent to a 1-cycle cosine filter with 64 samples per cycle for phasor estimation. The implemented cosine filter is similar to the one described in [16]. Each estimated phasor is divided by the gain of the low-pass filter at its respective frequency.

For calculating the differential and restraint currents using (1) and (2), respectively, it is necessary to correct the angular displacement of the input currents. This is done using the compensation matrices defined in [4]. The differential and restraint currents are then compared following an operation characteristic similar to that shown at Fig. 4. If the operating region is reached, the pick-up signal is set to 1. Otherwise, it is set to 0. Then, this pick-up signal is integrated and if the result reaches 2 it generates the trip signal, such as shown in Fig. 4. If the result of this integral becomes less than zero, it is setted to zero because it could not have a negative value.

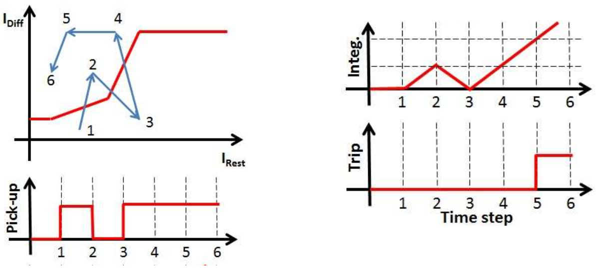


Fig. 4. Integration procedure used by the implemented relay model.

The c constant in (5) is given by [4]

$$c = \frac{100}{PCT\,2} \cdot I_{diff\,2} + \frac{100}{PCT\,4} \cdot I_{diff\,4} \qquad (12)$$

where I_{diff2} e I_{diff4} are the second and the fourth harmonic contents of the differential current. PCT2 and PCT4 are the reference settings used by the relay. All relay settings used in this study are listed in Table VI.

TABLE VI – SETTINGS OF THE RELAY MODEL

Settings	Setting Description	Value
CTR1	Current transformer ratio of primary winding	60
CTR2	Current transformer ratio of secondary winding	160
CTR3	Current transformer ratio of tertiary winding	400
TAP1	Tap value of primary winding	2.91
TAP2	Tap value of secondary winding	4.36
TAP3	Tap value of tertiary winding	4.36
W1CTC	Compensation matrix of primary winding	11
W2CTC	Compensation matrix of secondary winding	11
W3CTC	Compensation matrix of tertiary winding	0
O87P	Minimmun differential current	0.35
SLP1	Slope of the first section	30
SLP2	Slope of the second section	60
IRS1	Restraint current that divides first and second section	6
U87P	Unrestrained differential element pickup current	10
PCT2	Reference percentage of second harmonic content	20
PCT4	Reference percentage of fourth harmonic content	10
HRSTR	Enables harmonic restraint technique	Y
IHBL	Enables independent harmonic blocking (if setted as "N" the crossblocking method is used)	Y

B. Monte Carlo Method

The behavior of a differential relay during a specific phenomenon can be defined by a binary function $f(\eta^a)$. This function can be set to 1 if the relay operates properly and to zero if it fails. However, the argument η^a of this function is a vector of random variables, which makes the Monte Carlo Method particularly suitable for a systematic analysis of the relay behavior and for an estimate of its reliability.

In this study, the reliability of the differential function performed by the relay model is calculated for four different events: transformer energization, external faults, faults at the transformer bushings, and turn-to-ground faults. For each event, it is possible to define a different set of random variables that compose the arguments of vector η^a. For instance, for an energization study, the vector η^a can be represented as (13). The first element of this vector defines the closing time of the circuit breaker pole of the phase A. The second and the third elements define the difference between the closing time of the circuit breaker pole of phase A and phases B and C, respectively. The last three elements define the residual flux of the three phases. In (13), t_{pre} is the pre-energization time and $\phi_{\max}$ is the peak magnetic flux. $U(a,b)$ is a uniform random variable, in which a and b are the minimum and maximum values, respectively. $N(\mu, \sigma)$ is normal random variable with mean μ and standard deviation σ.

$$\eta^a = \begin{bmatrix} \eta_1^a \\ \eta_2^a \\ \eta_3^a \\ \eta_4^a \\ \eta_5^a \\ \eta_6^a \end{bmatrix} = \begin{bmatrix} t_{pre} + \left(\frac{U(0,1)}{60}\right) \\ N(0,\sigma) \\ N(0,\sigma) \\ \phi_{\max} \cdot U(0,1) \\ \phi_{\max} \cdot U(0,1) \\ \phi_{\max} \cdot U(0,1) \end{bmatrix} \qquad (13)$$

After defining the random variables, the next step is to proceed with the generation of the random numbers that will be used at each simulation. To do this, the function *grand* available in Scilab is used [7].

After generating the random numbers, ATP data cards are created for each case by a Scilab routine, such as its .bat file. After this, the .bat file is automatically executed performing the simulation and the .lis output file is read back by the Scilab routine. Then, the behavior of the differential protection function is evaluated for each case. The number of required simulations is defined as follows: Since the function f is binary, the mean μ and variance σ^2 of the estimator of its performance can be calculated as (10) and (11), respectively [12].

$$\mu = p \quad (14)$$

$$\sigma^2 = \frac{p(1-p)}{n} \quad (15)$$

where p is the rate of correct operations and n is the number of performed simulations. If the success rate P of the differential function is calculated as the rate of correct simulations p, the failure rate λ and reliability R can be calculated according to (7) and (8).

Following (15), there is a relationship between the number of simulations needed and the standard deviation σ. Thus, for a given standard deviation, the number of needed simulations can be calculated as

$$n = \frac{p(1-p)}{\sigma^2} \quad (16)$$

However, the number of simulations depends of the rate of correct operations, and this rate changes at each simulation. So, an iterative procedure was used to define the number of simulations [13]. The sequence of operations used in this procedure is shown in Fig. 5.

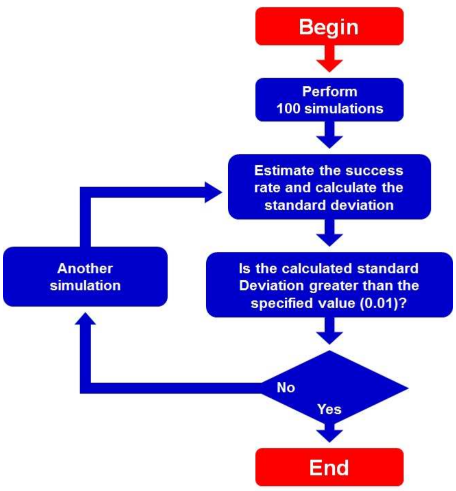


Fig. 5. Iterative procedure that define the number of simulations

Finally, the value of the success rate is presented with its error margin. In this study, a three standard deviation error margin is used.

V. Application of the Proposed Method

To evaluate the proposed method, simulations were performed for testing the reliability of the differential relay protection of the power transformer described in Section IV-A in four different conditions: transformer energization, external faults, faults at the transformer bushings, and turn-to-ground faults. The obtained results are presented in the following sections. Details of the transformer and networks parameters, as well as the relay basic settings are presented in Section IV.

A. Transformer energization

To evaluate the reliability of the relay protective function during transformer energization, simulations were performed considering three different inrush detection techniques discussed in Section II, namely harmonic restraint, independent harmonic blocking, and harmonic crossblocking. Table VII lists the obtained results, where it is shown that the best technique to prevent undesired relay operation during transformer energization is the crossblocking. However, this technique may block the relay incorrectly when the energization occurs under a phase-to-ground or a phase-to-phase fault due to the characteristic behavior of the healthy phases [14].

TABLE VII
Predicted Success Rate for Three Different Inrush Detection Techniques Implemented in the Relay Model (See definition of parameters HRSTR and IHBL in Table VI)

Technique	HRSTR	IHBL	Number of simulations	Success Rate (%)
Harmonic Restraint	Y	Y	847	90.67 ± 3.00
Independent Harmonic Blocking	N	Y	2144	68.89 ± 3.00
Crossblocking	N	N	100	99.00 ± 2.98

(*) *The success rate is saturated in 100%.*

The reliability of the harmonic restraint technique together with the independent harmonic blocking for different adjustments of second and fourth harmonic components is evaluated in Table VIII. According to Table VIII, the best results are obtained when the reference harmonic rate of second and fourth harmonic is set to 15% and 10%, respectively. It also suggests that these values should be adjusted as small as possible, taking into account the limits of the acquisition system (current transformers accuracy and relay A/D converters resolution). However, additional tests have to be performed to ensure that this set of parameters will not block the relay incorrectly during a fault condition. It is also worth noting that the use of the fourth harmonic content seems a very useful feature, although many relay manufacturers do not use it.

TABLE VIII
SUCCESS RATE OBTAINED USING DIFFERENT HARMONIC REFERENCE SETTINGS IN THE HARMONIC RESTRAINT TECHNIQUE (SEE DEFINITION OF PCT2 AND PCT4 IN TABLE VI)

PCT2	PCT4	Number of Simulations	Success Rate (%)
20	15	1176	86.39 ± 3.00
20	10	847	90.67 ± 3.00
15	10	327	96.64 ± 3.00

B. Turn-to-ground faults

Table IX shows the success rate obtained for turn-to-ground faults using two different minimum differential settings in a percentage restraint differential protection scheme. In the analysis, the same set of parameters listed in Table VI was considered, except for parameter O87P, which varied from 0.35 to 0.5. According to Table IX, a reduction in the value of the minimum differential current increases the reliability of the differential function during turn-to-ground faults. However, it increases the risk of misoperation due to noise in the secondary circuit of current transformers. Furthermore, the obtained values suggest that percentage restraint differential protection is possibly not a good technique to detect turn-to-ground faults.

TABLE IX
SUCCESS RATE OBTAINED USING DIFFERENT HARMONIC REFERENCE SETTINGS IN A PERCENTAGE RESTRAINT DIFFERENTIAL PROTECTION SCHEME (SEE DEFINITION OF PARAMETER O87P IN TABLE VI)

O87P	Number of simulations	Success Rate (%)
0.35	1831	75.87 ± 3.00
0.5	2116	69.61 ± 3.00

It is important to point that the vector of random variables for turn-to-ground faults contains five elements that define the winding and the phase under fault, the percentage of the winding in which the fault occur, the fault resistance and its time instant. So, during simulations mentioned in Table IX, many different situations were evaluated.

C. External faults and faults in the internal bushings

For external faults and internal bushing faults, the obtained reliability was 100%. This was expected because transformer differential protection was designed taking into account basically these two conditions. However, it is important to note that this result could be different if the magnetization branch of the current transformers was taken into account during modeling.

VI. COMPARISON WITH EXPERIMENTAL DATA

The Scilab routine stores all output files of cases classified as unsuccessful in the form of .pl4 files. When the settings of table VI were used, 847 cases of transformer energization were performed, with 79 unsuccessful cases. To evaluate the validity of the implemented relay model, the output currents associated to such unsuccessful cases were applied into a real digital differential relay using a power system simulator. In 67 out of these 79 cases a trip signal was sent by the relay, which was its expected behavior. This result shows that the relay model seems to be sufficiently accurate, although improvements could be made provided additional information on the relay algorithm were made available by its manufacturer.

VII. CONCLUSIONS

This paper presents a time-domain methodology to evaluate the reliability of a transformer protection differential function. To account for the random nature of many factors that affect the protection behavior, concepts related to the Monte Carlo method and reliability theory were used. The proposed method seems promising in the sense that it gives to the user a more precise idea of the expected behavior of the differential relay under different conditions. Moreover, it allows the user to test many different relay settings to choose the ones that are more adequate for a given application. Future studies with more detailed transformer and relay models, as well as with the inclusion of current transformer models, are in due course.

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