

STATISTICS OF SHORT-CIRCUIT SIGNALS FOR POWER SYSTEM PROTECTION PURPOSES

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Abstract – Basic ideas of probability and statistics with application to chosen power system protection problems are presented. Since fault appearance and parameters are of probabilistic nature, calculated distributions of selected short-circuit signals should bring great amount of information useful for protection purposes. Two examples are described how calculated statistics may be used for decision making in a fault detection and classification unit and for effective choice of optimal input signals in an ANN-based out-of-step prediction scheme. The short-circuit cases for determination of needed distributions were obtained performing extensive simulations with use of EMTP/ATP programme.

1. INTRODUCTION

To assure uninterrupted delivery of electrical energy to customers and to minimise losses caused by presumable system disturbances, protective relays are designed and installed in substations. Modern protective and control devices perform their functions nowadays in digital technique. It has been proved that considerable improvement of operation as well as quite simple achievement of adaptive features of protection functions may be obtained with use of various artificial intelligence (AI) techniques [1]. Artificial Neural Networks (ANNs) and Fuzzy Logic (FL) seem to be the ones with highest potential for solving complicated and non-linear protection problems. Design of an effective AI-based protection system, however, relies upon disposal of an extensive base of recorded or simulated power system fault cases. The ANNs have to be trained and FL membership functions appropriately tuned for given task with use of the signals constituting the data base.

Having gathered a number of simulation cases covering (to the highest possible extent) the variety of situations that can happen in real life, the statistical properties of various features can be analysed. In this paper the usefulness of probability density functions (PDFs) for realisation or improvement of two selected protection tasks is presented. In the case of both novel ANN-based out-of-step (OS) protection [2] and fault detection and classification (FD&C) scheme [3], the calculated statistical indices were used for effective choice of the algorithm input signals. The optimality of accomplished choices was confirmed by extensive tests of designed protection schemes. As shown in case of the presented FD&C scheme the statistical information (PDFs) may be utilised not only for preliminary design analysis but may also be processed with appropriate statistical algorithms in order to generate the final protection decision. The modified algorithm of the sequential probability ratio test (SPRT) [3] occurred to be an effective inference engine having features comparable to novel ANN-based fault classifiers. The following sections of the paper present main assumptions and key features of both protection schemes mentioned above. Results of simulative investigations and statistical analysis are also given and thoroughly discussed.

2. PDFs FOR OPTIMAL CHOICE OF PROTECTION CRITERION VALUES

The design of a new or improvement of existing protection schemes is a challenging task even for an experienced protection engineer or researcher. The theoretical analyses have to be very often supported by simulative investigations, especially in case of non-linear objects and complicated power system configurations. The simulation runs, if properly thought over, should deliver the

designer an enormous amount of information on the investigated events. The picture may be completed with the real world signals from digital recorders installed in substations. The latter may also be used for further testing of designed units.

Having gathered the comprehensive base of simulation cases one has to elaborate the available data to extract needed information. It is good practice to employ the statistical tools for that purpose and to calculate the probability density functions (PDFs) or other statistics of the features having (at least at the first sight) the highest strengths in given task.

The accuracy of PDF's calculation is a non-linear function of the number of simulation runs. Based on some statistics referring to the mean value and variance of distribution (assuming that a PDF is of normal type [4]) it can be found that about 1000 simulation cases are needed to calculate required PDF with 5% accuracy (by confidence level 0.95). To achieve 10% preciseness 200 cases are needed. Naturally, the higher preciseness is obtained the better results of further processing may be expected. In some cases, however, when the calculated statistics are only used to order the acquired knowledge, no high accuracy is needed.

A difficult problem, especially by new protection principles or non-standard processing (e.g. AI methods) is how to choose a proper decision signal for given protection task. The author's previous experiences in the field of ANN usage have shown that in order to obtain good effectiveness of pattern recognition, the features used as ANN input signals for both (or more) event classes should differ from each other to the highest possible extent. To avoid mistakes or disoptimalities often met by intuitive choices, the probability theory can be employed and calculated statistical indices may be used. Having prepared the conditional probability density functions (PDFs) of considered decision signals, probabilistic measures of their difference (or distance) can be calculated.

For proper choice of one specific decision value among a set of possible ones, the following time-dependent distance factors Δ between PDFs (X_0 , X_1) are suggested [2, 5]:

- difference of PDF expected values

$$\Delta_1(k) = E[X_0(k)] - E[X_1(k)] \quad (1)$$

- difference of PDF standard deviations

$$\Delta_2(k) = st_dev[X_0(k)] - st_dev[X_1(k)] \quad (2)$$

- cumulative mean of the product of latter two indices

$$\Delta_3(k) = \frac{1}{k} \sum_{i=1}^k [\Delta_1(i) * \Delta_2(i)] \quad (3)$$

- maximum of PDF difference squared

$$\Delta_4(k) = \max \left\{ [X_0(k) - X_1(k)]^2 \right\} \quad (4)$$

It is obvious that the best recognition efficiency will be achieved for a decision signal with the highest value of distance Δ . An ideal criterion value would be such where conditional PDFs are completely separated one from another. In such case a decision would be issued with 100% of probabilistic confidence.

In next sections application of the Δ factor method for the choice of criterion values in AI-based and statistical reasoning schemes is described. The PDFs acquired by simulation of numerous short-circuit cases are also used as parameters of decision-making algorithm based on hypothesis testing.

3. DESIGN OF THE NEURAL OUT-OF-STEP PROTECTION SCHEME

This section presents main features of the novel ANN-based OS protection scheme developed by the authors and described in detail in [2]. The new AI-based protection ensures faster and more secure detection of generator loss of synchronism when compared to traditional solutions. The OS conditions may occur due to loss of excitation or pole slipping. Both effects mentioned may threaten power system stability and cause severe mechanical and thermal stresses to the generator itself.

Various methods for the detection of loss-of-excitation and pole-slipping have been developed and are still in use in protection practice. Among others, the following are worth to be mentioned [2, 6]: tracking trajectory of the impedance vector measured at the generator terminals, methods based on the equal area criterion, direct method of Liapunov, rate of change of apparent resistance augmentation or observations of the voltage phase differences between substations.

Since the commonly used methods of loss of excitation and pole slipping protection are not always fast, precise and secure enough, new solutions applying AI approach are investigated. Hence, appropriate relaying procedures were considered and adequate ANN based solutions were developed and tested.

3.1. ANN-based OS protection

Artificial Neural Networks (ANN) represent a modern and sophisticated approach to problem solving for power system protection and control applications. The ANNs perform actions similar to human reasoning which rely on experience gathered during so called training. Advantages of ANN computing methodologies over conventional approaches include faster computation, learning ability, robustness and noise rejection.

While preparing useful and efficient ANN-based classification/recognition unit, one has to take into consideration at least the following design issues:

- ANN choice (ANN structure type, number of layers and neurones, neurone activation functions, ANN input signals),
- ANN training (training algorithm, initial values of synapse weights and biases), etc.

The ANN input signals have to be chosen in such a way that they provide maximum information suitable for solving of given protection task. This choice has been done experimentally, with assistance of calculated distance indices between conditional PDFs of six various considered criterion values.

Choosing the type of ANN structure and its further parameters is rather a matter of the designer experiences with ANN usage since, unfortunately, there are no general practical rules that could be applied for that purpose. The experimental way with sequential trial-and-error attempts can be followed, however, this may not guarantee the optimal ANN structure to be found.

To determine the most suitable neural network topology a genetic algorithm can be applied. At the beginning a so called initial population of neural networks is randomly created. The individual networks are trained with selected typical patterns and validated with all available patterns. After the quality of each network was determined an intermediate population is created on which several different genetic operations (crossovers, mutations, recombinations) can be applied to create a new population. The newly created population is trained and validated again and the process is repeated until the optimal ANN structure is found.

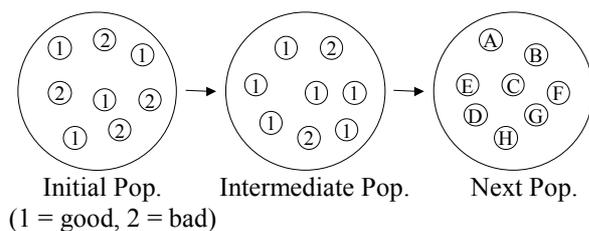


Fig. 1. Principle of the evolutionary process to optimise a network topology.

In design phase of the OS protection scheme numerous three-layer non-linear feed-forward neural networks (Multilayer Perceptron type) have been examined. The ANNs of various size have been trained and tested with use of MATLAB programme. From a total of 720 different network configurations examined the optimal ANN structure having 9-9-1 neurones was found.

The ANNs were trained to produce output equal to 0 for stable patterns and 1 for OS conditions. For classification purpose a threshold value set to 0.5 was introduced. All the cases for which the ANN output was lower than 0.5 were classified as stable and those for which the threshold was exceeded were recognised as OS cases.

The general scheme of the developed neural OS protection is shown in Fig. 2.

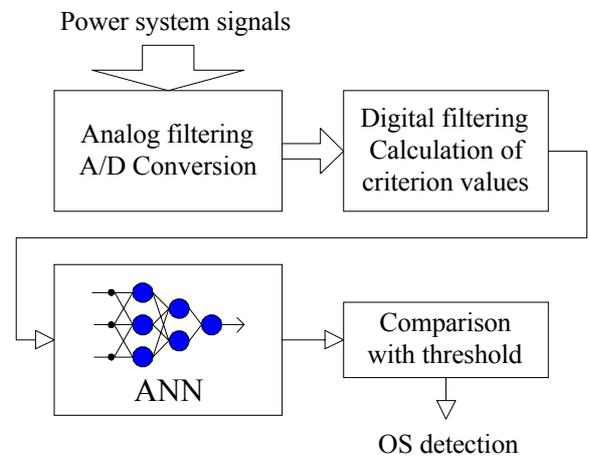


Fig. 2. Neural OS protection arrangement.

The designed neural OS scheme was then put to extensive tests. Promising results with regard to the detection speed and classification efficiency have been achieved. The developed scheme proved also to be robust against changes in fault conditions and synchronous machine ratings [2].

3.2. Data for ANN training and testing

To obtain data for training of ANNs and further testing of the OS protection, the following simple single machine – infinite bus system has been modelled (Fig.3) with use of EMTP/ATP programme.

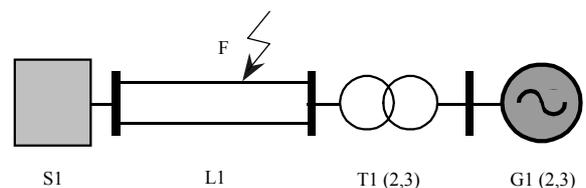


Fig.3. Fragment of power system modelled.

The synchronous machine G1 is connected to the infinite bus system S1 via the block transformer T1 and a 200 km long double-circuit line L1 on which different fault events are assumed to occur. Within the transmission line L1 different three-phase faults on one of the line circuits were applied. A total of 108 short-circuit cases were simulated with the fault parameters being varied:

- fault duration time (80, 100, 120 ms),
- fault termination (self-extinction, switching-off the faulty circuit, switching-off + reclosing),
- machine loading (0.1 ... 1.1 times rated power).

Generator output voltages and currents as well as its angular speed were registered in EMTP output files. Additional feature signals like voltage/current amplitudes, components of generator power etc. were obtained after digital processing of voltages and currents with use of standard algorithms [7].

In Fig. 3 some exemplary signals are shown for both stable cases and OS conditions for the time during (100-200 ms) and after (200-2100 ms) a short circuit. It may be observed that for stable

cases each of the signals presented tends to a new equilibrium point after a shorter or longer swinging transient period.

When OS conditions take place the synchronous machine accelerates and both the machine angle (Fig. 4a) and the impedance angle (Fig. 4b) begin to increase with a speed depending on machine loading, its kinetic energy, average acceleration during fault etc. In such cases also the voltage controller is no longer able to maintain generator terminal voltage at stable level (Fig. 4c). Theoretically, each of the signals presented may be used as a discriminative quantity for an OS detection scheme since, at least after fault clearance time, significant difference can be seen for both classes of phenomena.

In order to choose the best signals for application as ANN input features, the statistical properties of available signals have been determined. The calculations have been performed for such decision quantities as: machine angular frequency deviation $\Delta\omega$, impedance angle $Arg(Z)$, active power P , reactive power Q , resistance R and reactance X (measured at the generator terminals from machine phase currents and voltages).

The mean and maximum values of calculated statistical distance measures over considered time range (0.24-1.44 s after fault switching-off) are shown in Table 1. The analysis of the statistics obtained allow the sorting of decision signals according to their relative recognition strength. The greater distance coefficients, the higher the ranking position. In the investigated case the most valuable recognition feature turned out to be the angular frequency deviation, followed by the impedance angle and reactive power measured at the machine terminals. The statistics for the remaining signals do not promise good classification abilities.

Table 1. PDF distance for various decision signals.

PDF distance	Decision signal					
	$\Delta\omega$	$Arg(Z)$	P	Q	R	X
mean (Δ_1)	0.31	0.20	0.14	0.24	0.07	0.04
max (Δ_1)	0.66	0.60	0.22	0.39	0.10	0.11
mean (Δ_2)	0.07	0.07	0.02	0.04	0.02	0.03
max (Δ_2)	0.10	0.10	0.03	0.06	0.07	0.08
mean (Δ_3)	1.04	0.49	0.17	0.75	0.18	0.33
max (Δ_3)	2.64	1.78	0.22	0.98	0.26	0.57
Ranking	1	2	5a	3	5b	4

The average results of OS detection for considered ANN input features are given in Table 2. The results obtained for various ANN input signals confirmed our previous expectations as to their recognition abilities assessed with use of proposed

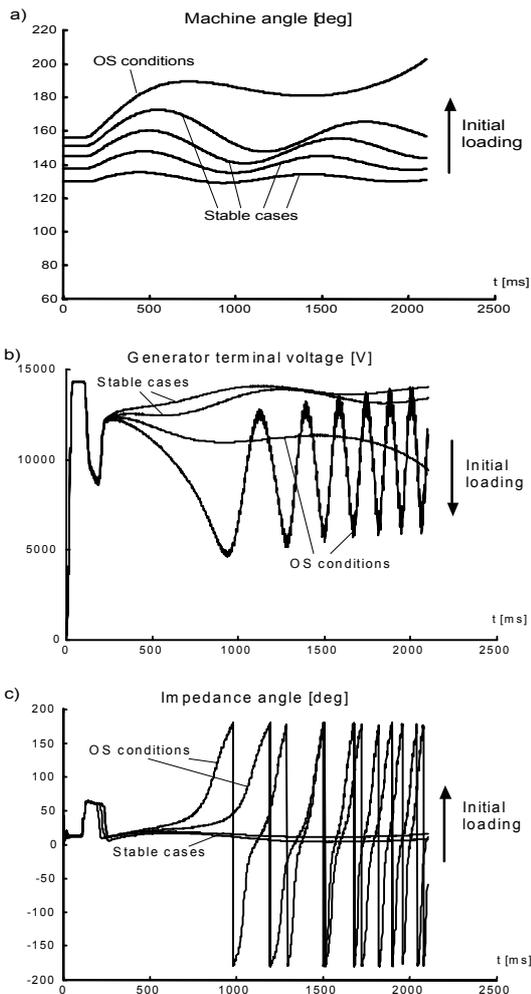


Fig. 4. Exemplary machine signals for stable cases and OS conditions: a) machine angle, b) generator terminal voltage, c) impedance vector angle.

Table 2. Average values of relative classification errors [%] for
a) training data set

Input signal	ANN window length [s]					
	0.24	0.48	0.72	0.96	1.20	1.44
$\Delta\omega$	5.6	0.6	0	0	0	0
$Arg(Z)$	6.7	0.6	0	0	0	0
P	6.7	2.6	3.5	3.7	0	0
Q	6.5	2.0	0.2	0.2	0.2	0.2
R	18.7	14.0	10.2	4.3	0.6	0.6
X	19.4	17.8	16.1	11.8	11.7	5.7

b) testing data set

Input signal	ANN window length [s]					
	0.24	0.48	0.72	0.96	1.20	1.44
$\Delta\omega$	5.9	0.8	0.2	0	0	0
$Arg(Z)$	6.5	1.2	1.0	0.8	0.8	0
P	6.0	5.0	5.3	5.1	1.7	0.3
Q	6.7	4.1	1.8	0.6	1.0	1.8
R	18.3	13.0	8.0	4.2	1.3	1.1
X	18.0	16.5	15.1	13.5	15.9	11.7

statistical indices. The best classification efficiency was achieved for ANNs fed with $\Delta\omega$ and $Arg(Z)$ signals. For these features no false recognitions for training set cases were observed after 0.6 sec and less than 1% of errors for 0.48 sec data window. Testing the designed ANNs with signals not presented during training (testing data set) brought very good results - 1% or less mis-classified cases at 0.48 sec after fault clearance. It means that the developed neural scheme was able to detect the OS conditions (predict it) when no significant OS symptoms were yet visible which is not possible with use of standard OS protection methods.

One can observe that the ANN efficiency is time dependent and increases when longer data window is applied. This is an effect of processing larger amount of information also from the period when the OS symptoms are more clearly visible in the input signals.

4. DETECTION AND CLASSIFICATION OF FAULTS WITH STATISTICAL METHODS

Digital protective relays generate their final decision by making a comparison of some calculated on-line criterion values and pre-set thresholds or characteristics. In order to work correctly, however, the measurement phase is usually preceded by some auxiliary procedures including fault detection and classification (FD&C).

These pre-processing procedures are more or less important from the point of view of overall relay reliability. If an actual fault is not recognized by

the fault detecting procedure, the relay is not activated. Errors in proper detection of fault instant may also cause maloperations of measuring units if it is based on methods requiring knowing the disturbance beginning, like Kalman filter based methods for impedance measurement or some of directional and distance elements that require pre-fault values of certain signals. False fault classification may also be a source of serious maloperations of a distance relay consisting of a single measuring unit where certain linear combinations of phase signals (different for various fault types) are required to calculate the positive sequence impedance. The information concerning phases involved in a fault is also needed when the single-pole autoreclosure unit is to be installed on a line.

In digital relays the FD&C procedures are realized with use of the algorithms watching samples of phase currents and/or voltages (not-processed signals) or some calculated values like phase impedance components. In use are also relatively new methods based on fuzzy logic or artificial neural networks. In the next section a probabilistic classification method based on hypothesis testing is presented and some optimization aspects of the method are discussed.

4.1. Probabilistic FD&C scheme

The block scheme of developed FD&C procedure is shown in Fig. 5. The scheme makes use of the statistical hypothesis testing method - sequential probability ratio test (SPRT). The SPRT belongs to statistical decision-making methods in which number of samples necessary to issue a decision is not pre-defined. In order to generate a decision the algorithm utilizes information from the conditional probability density functions (PDFs) of the decision vector for given classes of events. The procedure minimizes values of the first and second order error probabilities [8].

Three simultaneously operating SPRT blocks (SPRT1 - SPRT3) are applied for phase signals to indicate which phases are involved in a fault (SPRT equipped with PDFs referring to normal operation state and fault conditions). The fourth SPRT block (SPRT4) discriminates whether a ground fault occurred (PDFs for ground and isolated faults). The Logic and Control Unit (LCU) realizes:

- determination of the fault instant and type (on basis of the outputs of four individual SPRT blocks),
- coordination of SPRT blocks operation (commands to block and restart the sequential testing procedures),

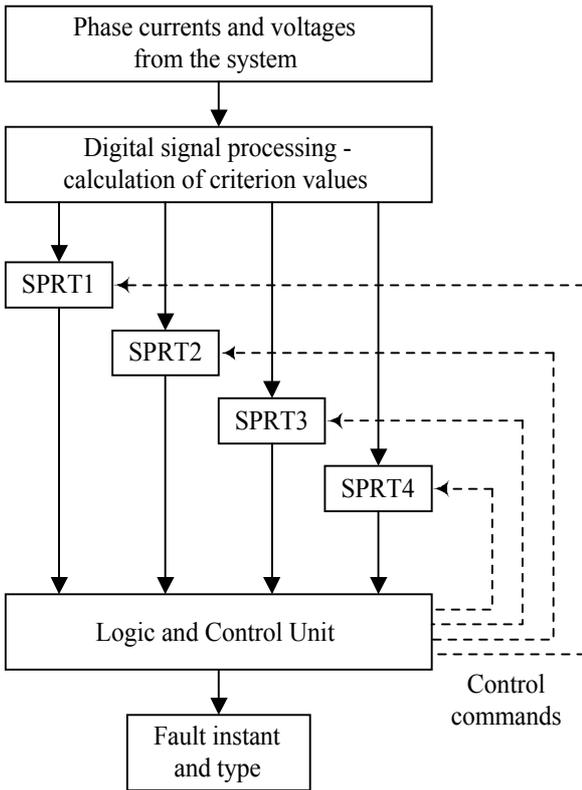


Fig. 5. Block scheme of the statistical FD&C.

- on-line correction of SPRT parameters (setting the time instant in blocks remaining in testing transient state).

More details on the statistical FD&C scheme can be found in [3].

4.2. Statistical assessment of the scheme

To generate data for optimization analysis and testing of the developed FD&C method the EMTP/ATP model of a fragment of 400kV transmission power system was used (Fig. 6).

Within overhead line L_{CD} a set of 864 faults have been simulated where parameters being varied for each simulation run were:

- magnitude and phase value of system S_A voltage,
- fault angle,
- fault resistance,
- fault location,
- fault type.

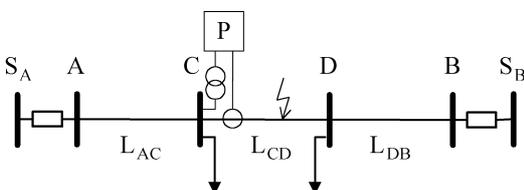


Fig. 6. Single line diagram of test power system.

Phase currents and voltages at the relaying point P were recorded and chosen criterion values for fault detection and classification were calculated. On basis of the recorded signals the conditional probability density functions of criterion values for successive time steps after fault instant were calculated.

Many criterion values were considered as decision variables for application in our FD&C scheme. Among them were for example: magnitudes of phase currents and voltages, their symmetrical components, phase impedances etc. With help of factor Δ (distance between PDFs) the best decision variables for the task were chosen, namely phase impedances - for faulty phase (-s) selection and zero-sequence current magnitude - for discrimination between ground and isolated faults.

To illustrate the choosing method with Δ factor, the distance between PDFs for hypothesis $H_0 =$ „fault“ and $H_1 =$ „normal operation“ is shown in Fig. 7 for criterion values: phase current magnitude and phase impedance. A big difference in the steady-state values of distance to the advantage of impedance Z_{L1} can be seen. Application of this value as decision variable in SPRT test should bring better results if both speed and accuracy of the decision process are considered.

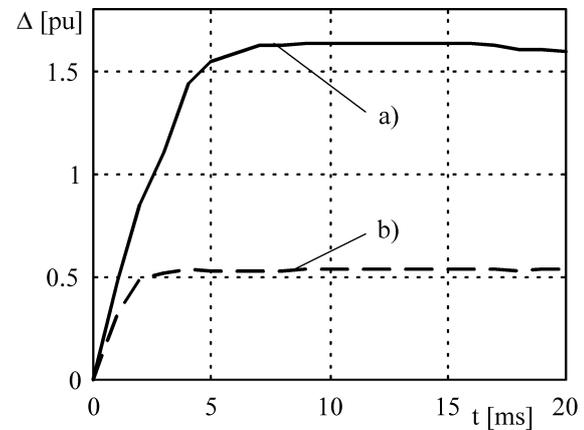


Fig. 7. Distance Δ (eq. (4)) between PDFs for criterion values: a) Z_{L1} , b) I_{L1} .

The influence of measurement algorithm used to estimate criterion values on distance Δ dynamics can be seen in Fig. 8. The criterion values were obtained on basis of orthogonal components of phase currents and voltages with orthogonal transformation of signals made using time delay and by filtration with pair of half-cycle filters (sine and cosine data windows). The steady state value of Δ is the same for both algorithms, but the difference in dynamics due to impedance measurement transients can be observed. Lack of filtration in case of orthogonalization with time delay affects certainly the accuracy of measure-

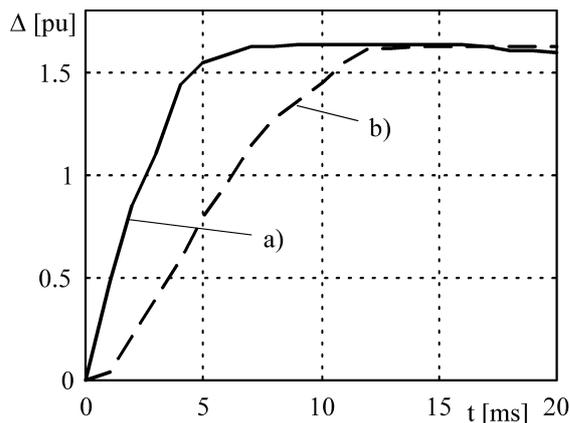


Fig. 8. Distance Δ (eq. (4)) between PDFs for criterion value Z_{L1} calculated with orthog. alg. using: a) time delay, b) half-cycle sin-cos filters.

ment especially when the signals are distorted by harmonics or DC component. Nevertheless, if only the conditional PDFs for distinguished hypothesis are sufficiently separated one from another (high enough value of distance Δ), the decision process will be efficient, independently on the accuracy of measurement.

Similar investigations including the choice of criterion values and measurement algorithms have been done for zero-sequence voltage and current (candidate variables for ground fault discrimination). Better results were obtained for zero-sequence current, thus this variable was accepted for application in the FD&C scheme.

After design phase, the FD&C scheme with statistically selected input signals was put to the extensive tests. The algorithm demonstrated excellent ability of fault detection. All simulation cases were detected properly, mostly in the first or second sample after fault inception. Fault classification was made with effectiveness of 97.2% and average time of 3 ms. The algorithm had some problems with distinguishing between line-line and line-line-to-ground faults at the end of the line L_{AB} and by high value of pre-fault load. The test results obtained for measurement algorithm with sine-cosine filters were a bit worse (exactitude lower, time longer) which is understandable having in mind previous optimality considerations.

The operation of the probabilistic FD&C scheme proposed has been compared with the ANN based method developed by our colleagues from Wroclaw University of Technology and described in [9]. The ANN fault detector consisted of four feed-forward neural networks, each with (10-5-1) neurons in input, hidden and output layers, respectively. The inputs of all ANNs were samples of current signals observed in half-cycle moving

data window. After the training phase, the ANN fault detector was tested. The overall accuracy of fault type classification reached value of 98.8%. False indications were generated in some heavy cases of line-line faults only (similar as by our statistical method).

The probabilistic FD&C algorithm proposed was successfully implemented on a rather slow signal processor TMS320 which proved the possibility of real-time application of the developed method.

5. CONCLUSIONS

The probability concepts have been proposed for realising effective choice of criterion values to solve two power system protection problems. Except for the statistical FD&C scheme mentioned, the Δ factor method was applied for optimal choice of the ANN input signals in the neural out-of-step protection scheme described. The choices accomplished with help of PDF distance factors proved to be the right ones according to the results of extensive tests of the developed OS protection. The relatively compact neural network (with 9-9-1 neurones in particular layers) was able to detect more than 99% of the simulated OS cases within 0.5 sec after switching-off the fault.

An example of a memory exhaustive (yet implementable) procedure – probabilistic FD&C scheme taking advantage of calculated statistical distributions of criterion values was described. With use of the statistics proposed thorough optimization analyses of the scheme were performed with regard to the decision signals and measurement algorithms applied. The final version of the scheme was tested showing very good speed and effectiveness of recognition process.

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