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Fault Diagnosis and Evaluation of the Performance of the Overcurrent Protection in Radial Distribution Networks Based on Wavelet Transform and Rule-Based Expert System.

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***Abstract*— This paper presents a fault diagnosis algorithm in radial distribution networks. The input data are the currents of the feeder per phase, monitored only in the substation. An algorithm based on Discrete Wavelet Transform (DWT) is used to detect, classify and locate the faults at the moment they occur. This algorithm takes advantage of the special properties of the wavelet transform to differentiate waves' signature produced by a system under normal conditions, under disturbances related to power quality problem and under faults involving short-circuit conditions. A rule-based expert system (RBES) is developed to evaluate the performance of the overcurrent protection system during a fault. The main application of the proposed algorithm is to assist in the operation during a fault, and supervise the protection system. Simulation results using ATP/EMTP for a 282-bus non-transposed real feeder are included.**

I. INTRODUCTION

An accurate and fast fault diagnosis in the distribution system is essential for electric utility to expedite the restoration of the service, reducing outage time, operating costs, and customers' complaints. In order to achieve these goals, the electric utilities have invested in optimizing theirs transmission and distribution systems and in automating their operations. The fault situation to be identified includes the information about where and what the fault is, i.e., the fault section and the fault type. Based on the alarm signals of the protection system, the operators of a substation are required to estimate the fault situation immediately after its occurrence. However, in the cases of multiple faults or failure of operation of the protective devices, the situation will lead to a large number of alarm signals. Over the past decade, considerable efforts have been made toward developing of faster and reliable computer tools for fault diagnosis. The first methods used in the fault diagnosis were mainly based on the power frequency components [1-2] and based on the fault-generated traveling waves [3-4]. The literature also proposes the use of artificial intelligence techniques for fault diagnosis. Among these techniques there are the artificial neural networks [5], fuzzy logic [6], genetic algorithms [7] and artificial immune systems [8]. Wavelet analysis of the fault-generated traveling waves to the fault diagnosis is proposed in [9-16]. This paper presents a real time fault diagnosis algorithm, where the discrete wavelet transform is used to detect and classify the fault. Additionally, DWT is used to register the behavior of the current wave after the fault and an RBES is used to evaluate the performance of overcurrent protection.

II. SOLUTION METHOD

The proposed algorithm is based on the monitoring of currents of each set of three-phase protection CTs installed in the substation. The computational routine uses sampled data windows from the secondary CTs. These data windows are processed by DWT and RBES in order to solve the problem of fault diagnosis. Its purpose is to assist the operation of the system and to increase its reliability by reducing the number and / or duration of the distribution system outages. Additionally, the algorithm produces a register of all events related to transient or permanent short-circuits that can be used for operation, planning and protection studies. This paper shows a potential tool to be used in the diagnosis of faults in distribution networks because it draws together four characteristics that differentiate it from other techniques shown in the literature:

1. While many techniques presented in the literature are not applicable to problems for real time implementation, the distinctive feature of the proposed wavelet-based method is the ability to detect and classify the disturbances in real-time.
2. While many techniques presented in the literature require measurements at various points in the power system or need to construct a distribution network simulation model, the proposed algorithm is based on real time measurements of 3 phase currents, monitored only in the substation.
3. This work differentiates short circuits from power quality problems.
4. In this work the currents signals are continuously monitored in real time, aiming to record meaningful alterations in their values. The analysis of the digital fault recorder is made by the rule-based expert system in real time and can identify problems in the protective devices coordination or mis-operation from recloser, sectionalizer or fuse.

A. Wavelet Transform

Most of the signals in practice are time-domain signals in their original format. In many cases, the most distinguished information is hidden in the frequency content of the signal. The frequency spectrum of a signal is basically the frequency components of that signal. In order to obtain the frequency content of a signal, the Fourier transforms is probably the most popular transform being used (especially in electrical engineering), but others transforms also can be used as Hilbert trans-

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form, short-time Fourier transform , Wigner distributions, Radon Transform and Wavelet transform. Every transformation technique has its own area of application, with advantages and disadvantages, and the wavelet transform (WT) is no exception. Like Fourier analysis, wavelet analysis deals with expansion of functions in terms of a set of basis functions. Unlike Fourier analysis, wavelet analysis expands functions not in terms of trigonometric polynomials but in terms of wavelets, which are generated in the form of translations and dilations of a fixed function called the mother wavelet. The wavelets obtained in this way have special scaling properties. They are localized in time and frequency, permitting a closer connection between the function being represented and their coefficients.

According to [5], Wavelet Transform is a recently developed mathematical tool which can be used for signal processing with a wide variety of applications, similar to the Fourier Transform. However, it is different from Fourier Transform because it allows time localization of different frequency components of a given signal. It provide simultaneous interpretation of the signal in both time and frequency domain which allows local, transient or intermittent components to be exposed. Wavelet Transform can be continuous or discrete. The continuous Wavelet Transform reveals more details about a signal, but its computational time is enormous. For most applications, however, the goal of signal processing is to represent the signal efficiently with fewer parameters and less computation time. DWT can satisfy these requirements.

The DWT output can be represented in a two-dimensional grid, similarly to the windowed-DFT (Discrete Fourier Transform), but with very different divisions in time and frequency. Filters of different cutoff frequencies are used to analyze the signal at different scales. The signal is passed through a series of high pass filters (hpf) to analyze the high frequencies, and it is passed through a series of low pass filters (lpf) to analyze the low frequencies. DWT can decompose the signal into various levels that represent the part of the original signal in that particular time and in that particular frequency spectrum. At each level, the high pass filter produces detailed information (d), while the low pass filter produces coarse approximations (ap). At each decomposition level, the half band filters produce signals spanning only half the frequency band. Fig. 1 illustrates this process that is known as Multiresolution Analysis (MRA) [17]. The decomposition process is continued until the desired level is reached. The maximum number of levels depends on the length of the signal. Note that due to successive subsampling by 2, the signal length must be a power of 2, or at least a multiple of the power of 2, in order for this scheme to be efficient. MRA is one of the most active branches of the Wavelet Transform theory. Introduced by Mallet [17] in 1989, the MRA provides an effective way to examine the features of a signal at different frequency bands. These features may be essential for pattern recognition. Hence, it is well suited for the fault identification and classification in the power systems.

There are a number of basis functions that can be used as the mother wavelet for Wavelet Transformation. Since the mother wavelet produces all wavelet functions used in the transformation through translation and scaling, it determines the characteristics of the resulting Wavelet Transform. Therefore, the details of the particular application should be taken into account and the appropriate mother wavelet should be chosen in order to use the Wavelet Transform effectively. Daubechies, Symlet and Coiflets mother wavelets have been more appropriate in the study of power quality [18]. In this paper the Daubechies 5 mother wavelet was used.

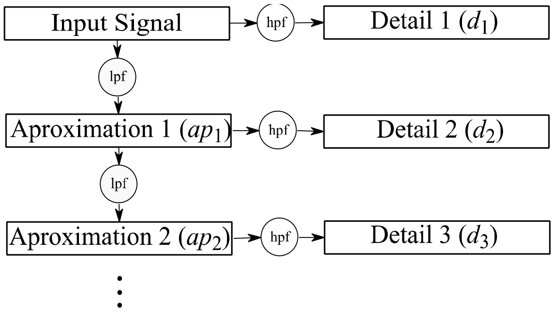

Fig. 1. Decomposition process of a signal through filtering process..

B. *Fault Detection and Classification Algorithm*

In this paper, the MRA is used to detect and classify faults in radial distribution networks. The input signals are the currents of each set of three-phase protection CTs installed in the substation.

Short circuits and power quality problems usually distort the sinusoidal waveforms of the electric supply. This characteristic is used by the proposed algorithm which detects faults by the difference between the detailed information of the input signal and the detail information of its fundamental frequency waveform, named Reference Signal (RS). The percentage difference in energy between the detailed information of RS and the detailed information of the input signal is defined by (1) and (2). From studies and experiments with several simulated cases, it was observed that especially in levels 6 and 7 the results obtained by (2) for the input signal containing short circuits were considerably higher than those produced by input signal without the presence of short circuits (first column of Table I). In this paper, the sum of the values of (2) produced at these two levels (6 and 7) was used to detect the presence of short circuits in the sampled signal. This is shown in (3).

$$E^n = \int_{-\infty}^{+\infty} \left| d[n] \right|^2 \tag{1}$$

$$\%\Delta E_n = \left| \frac{E^n_{\text{input signal}} - E^n_{\text{RS}}}{E^n_{\text{input signal}}} \right| * 100 \tag{2}$$

$$\%\Delta E = \%\Delta E_6 + \%\Delta E_7 \tag{3}$$

Where $d[n]$ is the detailed information of level n of a discrete signal; $E^n_{\text{input signal}}$ is the detailed information of the energy level n of the input signal; E^n_{RS} is the detailed information energy of level n of the RS; $\%\Delta E_n$ is the energy percentage difference between the detailed information of RS and the detail information of the input signal of level n.

Power quality problems also produce significant values of $\%\Delta E$. The first column of Table I shows the results of several power quality problems (PQ) and of a phase-to-ground short circuit. The short circuit is simulated at the farthest node from the substation, reproducing the worst case to detection due to low post-fault current. In order to differentiate short circuits from PQ problems were used (4) and (5) to calculate the maximum deviation between the input signal detailed information and the RS detailed information for a specific level. It was observed that the value of (5) is greater for input signals with short circuits than signals with PQ, even for the worst case simulated. The second column of Table I shows the values obtained by (5) with n=7 for various PQ and a phase-to-ground short circuit.

$$f_{\text{deviation}}^{n}(y) = \frac{\left| d[n]_{\text{input signal}}(y) - d[n]_{\text{RS}}(y) \right|}{Amp_{\text{RS}}} * 100 \tag{4}$$

$$D_n = \max(f_{\text{deviation}}^{n}) \tag{5}$$

Where y is a integer: y=1,…, the total number of samples in data window; $d[n]_{\text{input signal}}$ is the input signal detailed information of the level n; $d[n]_{\text{RS}}$ is the RS detailed information of the level n; Amp_{RS} is the amplitude of RS; $f^{n}_{\text{deviation}}$ is the deviation function between the input signal detailed information and the RS detail information for the level n; D_n is the maximum value of the deviation function.

TABLE I. RESULTS OBTAINED BY (3) AND (5) FOR SEVERAL DISTURBANCES.

Input signal	**%Δ*E***	***D*₇**
No disturbance	10.85	1.84
phase-to-ground short circuit	108.1	15.17
Harmonics (THDC=2.38%)	18.87	3.2
Fluctuation	11.18	1.57
20% SAG	53.18	2.59
50% SAG	158.18	5.8
20% SWELL	36.67	2.94
50% SWELL	77.44	2.45
Notching	9.42	1.23
Spike	11.19	2.02

The amplitude of RS is used for normalizing the deviation value. In this case, the value of (5) does not depend on the amplitudes of currents involved in the disturbance. This is important to establish values of (5) that differentiates short circuits from PQ problems independent of the level of currents involved. In the simulations, the level of decomposition that best distinguished short circuits from PQ problems was n = 7. Fig. 2 shows the values of (4) obtained from a phase-to-ground short circuit (Fig. 3) and a transient current (Fig. 4).

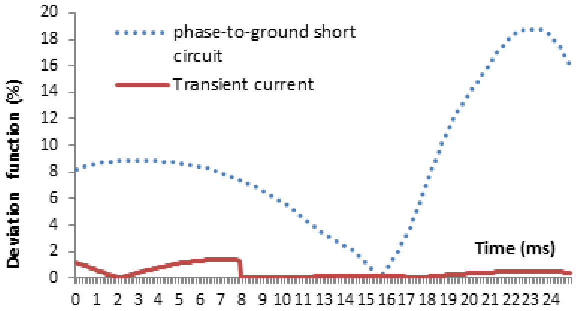

Fig. 2. Equation (4) applied in a phase-to-ground short circuit and a transient current.

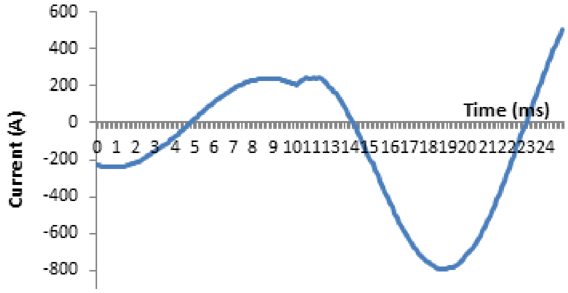

Fig. 3. A phase-to-ground short circuit.

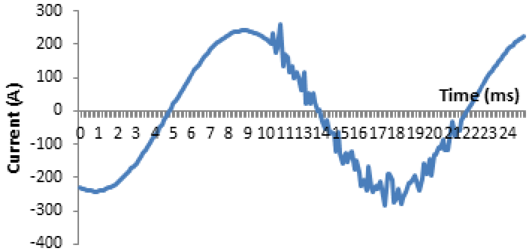

Fig. 4. A transient current.

According to simulations, %ΔE > 40 and D_7 > 12 were the limits adopted for characterizing a short circuit. The data windows taken in real time from the three-phase protection CTs installed in the substation are processed in order to solve the problem of the fault diagnosis. The size of the data window used is one and a half cycle assembled as follows: the latest input signal cycle taken plus the previous half cycle. This data window is used to detect more easily the faults that occur between the end of the previous cycle and the beginning of the current one (Fig. 5).

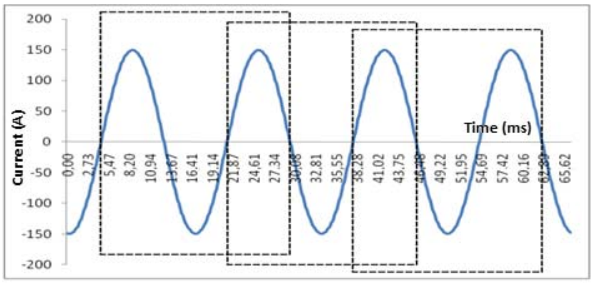

Fig. 5. Windowed scheme of the input signal for the detection of disturbance.

The RS used is 60 Hz pure sine. Fast Fourier Transform (FFT) is applied in the data window to determinate the amplitude of RS. FFT is applied to each data window taken. The data window and RS are synchronized in time through the phase. It is very important to obtain an accurate phase from the data window because a delay between the signals can cause a false detection. In this algorithm the moment of zero crossing is identified in the data window and based on this value the reference signal is shifted. Fig. 6 shows an example of this process. After fault detection, the short circuit is classified as follow: (1) identification of the quantity and which phases are involved in the short circuit through the data windows that detected the fault and (2) verification if the fault involves the ground when it is a phase-to-phase short circuit. The fault detection and classification is performed as illustrated in Fig. 7. After fault classification, the algorithm evaluates the performance of the overcurrent protection. The MRA from one of the data windows that detected the fault is the input data to this process.

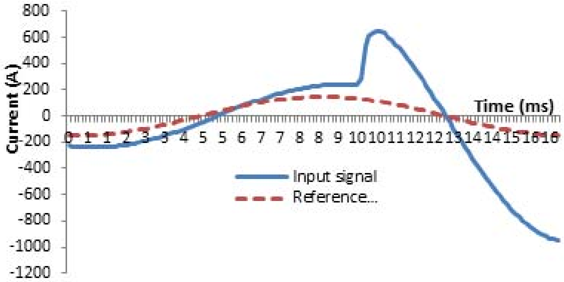

Fig. 6. Synchronization between the input and the reference signal.

C. *Performance of the Overcurrent Protection*

The purpose of monitoring the protection system is to check the speed and correctness of its operation. While evaluating the speed and correctness of the protection systems, the following items will be considered: did the protection systems operate as intended? Did the protection systems operate within the time limits? Did all protection systems react properly? Did reclosing operate as intended? The overcurrent protection usually used in radial distribution is reclosers installed in substations and fuses and sectionalizers installed along the network. The reclosers establish the maximum operating time of the protection system when dealing with a short circuit. The restore service time after a fault depends on the time of operation of the recloser, time duration of fault (transient or permanent fault), and the amount of sectionalizers and fuses installed upstream of the fault. For example, if the total time for the sequence of recloser operation for 10 s up to 600 cycles is needed after the fault for the complete analysis of its performance.

1) Recloser-sectionalizer-fuse coordination

A coordination study consists of the selection or setting of all series protective devices from the load upstream to the power supply. In selecting or setting these protective devices, a comparison is made of the operating times of all the devices in response to various levels of the overcurrent. The objective, of course, is to design a selectively coordinated electrical power system. In a traditional radial distribution network, the protection systems are designed assuming unidirectional power flow and are usually based on reclosers, sectionalizers and fuses. Reclosers are located in the main feeders to protect against transient faults. Sectionalizers are located downstream of a recloser to isolate the faulted section of the network after the specific number of recloser operations, leaving that part of the feeder upstream still in service. Fuses are located at the beginning of laterals and sublaterals to protect the system against permanent faults. The recloser-sectionalizer-fuse coordination is usually performed based on fuse-saving principles [19]. The main idea behind the recloser-sectionalizer-fuse coordination philosophy is that when a fault occurs, the recloser should operate in its fast mode and disconnect the circuit to give the fault a chance to clear. In case of a permanent fault, upon completion of the recloser's fast mode shots, the fuse blows to clear the fault while the recloser is waiting to operate on its slow curve. In case the fault still exists, the sectionalizer will open and isolate the fault after the specific number of opening of the recloser. In this paper the evaluation of the performance of overcurrent protection in radial distribution networks is presented considering recloser-sectionalizer-fuse coordination.

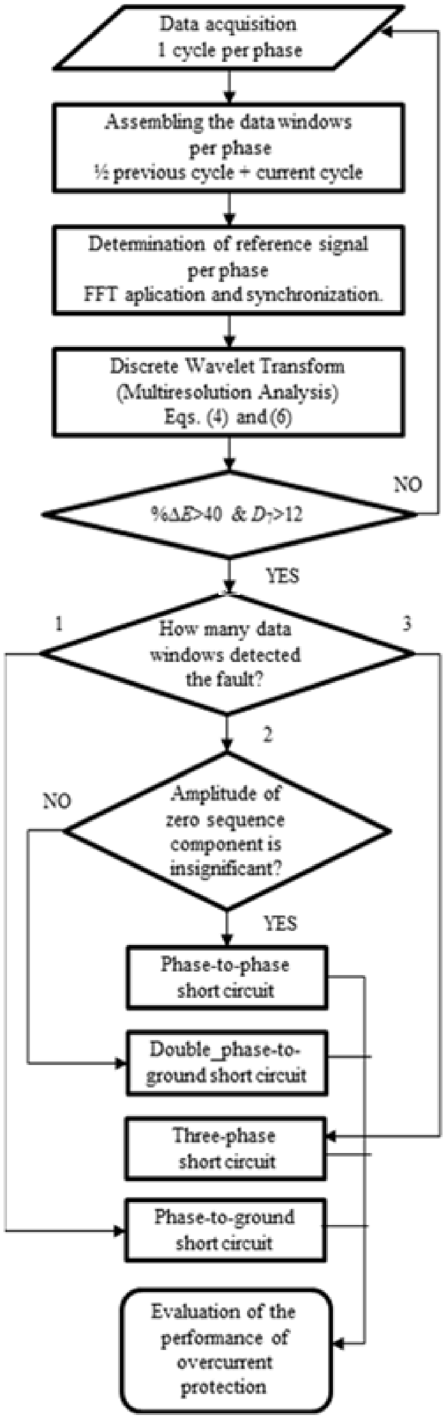

Fig. 7. Flowchart for fault detection.

2) *Identification of sudden changes in the input signal*

The detail information obtained from a signal contained short circuit shows peaks around the instant that sudden changes occur, such that they can be used to identify the time which the fault was initiated, the operating time of the protection system and if it was a permanent or transient fault. Examples are shown in Figs. 8-11 for transient and permanent faults. Fig. 8 shows the values of (4) for *n*=1 obtained from a transient fault (Fig. 9) without protection operation. Fig. 10 shows the values of (4) for *n*=1 obtained from a permanent fault (Fig. 11) with the protection operation. In both examples there is a set of peaks around the instant of sudden changes in the signal (Peaks Area – PA). In this algorithm, the maximum value (MV) from a PA is considered as the instant of sudden change in the signal and used as the parameter to identify the time when the fault was initiated and operating time of the protection system. These times are determined from the data window where the short circuit was detected plus several subsequent data windows. The number of subsequent data windows used in this process is defined by the dead time of the recloser. In order to find a PA and its respectable MV in a data window a sequential search in the function represented by (6) is performed.

$$\Delta D(y)=\frac{\left|d[1]_{\text{input signal}}(y)-d[1]_{\text{RS}}(y)\right|}{\max\left(\left|d[1]_{\text{input signal}}-d[1]_{\text{RS}}\right|\right)} \tag{6}$$

This function has values between 0 and 1. It is observed that the peaks from PA are not monotonically creasing or decreasing (Fig. 8 and Fig. 10), therefore, in this paper, *y* is only defined as a point of MV after at least *x* subsequent samples being smaller than it. From the studies *x* was defined as 5% of total number of samples in a data window. After determining MV, subsequent *z*-samples are skipped to start a new search to avoid search in the same PA. From the studies *z* was defined as 15% of total number of samples in a data window. To prevent that the sequential search does not find MV in peaks produced by noises (Fig. 8 and Fig. 10), *y* only is considered as a possible point of a MV if $\Delta D(y) > 0.25$.

In order to avoid peaks produced in the edges of the data window due to discontinuance, a range around the edges is not considered by sequential search. The range adopted was 10% of total number of samples in the data window. This procedure does not compromise the sequential search because the edges from the current data window are within the search area of previous and subsequent data windows. This part of the algorithm is performed as illustrated in Fig. 12. After concluding the dead time of the recloser is performed the evaluation of the performance of the overcurrent protection based on a rule-based expert system that is described in the next section.

When a transformer is first energized, an inrush current up to 10 to 15 times larger than the rated transformer current can flow for several cycles. To accommodate this inrush current, the fuse curve should be to the right of the transformer inrush point and to the left of the cable damage curve. In fault diagnosis is important discriminating an inrush current from transient faults. In this paper, to discriminate inrush current from the other transients was used the methodology presented in [20] that uses the sum of the absolute of detail-6 in MRA for three phase currents. If an inrush current is detected the ICD index (Inrush Current Detection) is set to true.

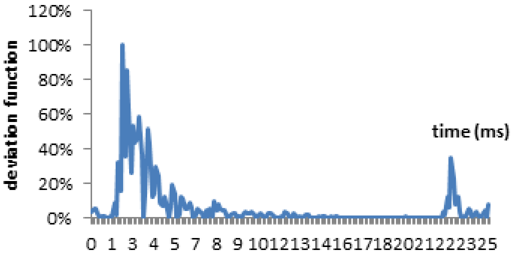

Fig. 8. Equation (4) applied to a data window with transient fault.

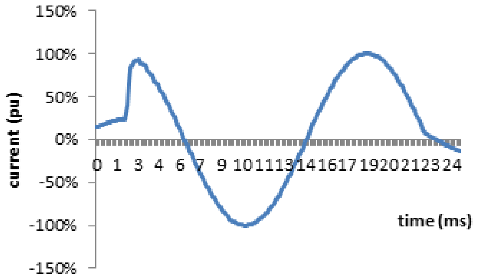

Fig. 9. A transient fault.

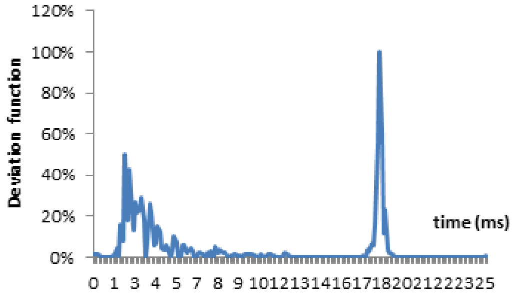

Fig. 10. Equation (4) applied to a data window with permanent fault.

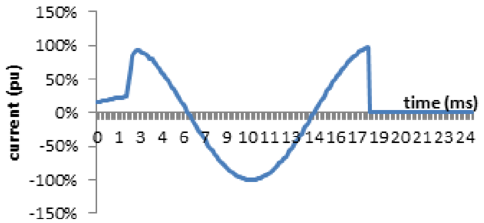

Fig. 11. A permanent fault.

3) *A rule-based expert system to evaluate the overcurrent protection operation*

Conventional rule-based expert systems use human expert knowledge to solve real-world problems that normally would require human intelligence. Expert knowledge is often represented in the form of if-then rules. Rule-based expert systems have played an important role in modern intelligent systems and their applications in strategic goal setting, planning, design, scheduling, fault monitoring, diagnosis and so on [21].

In this paper, a rule-based expert system is proposed to evaluate the performance of the overcurrent protection in radial distribution networks. The rule-based expert system used considered the recloser-sectionalizer-fuse coordination and two fast and two delayed recloser operations. The set of rules is developed considering all possible protection system operation in this situation. It was considered the expertise knowledge about the protection system operation. The proposed of the rule-based expert system is, after fault, to show in real time the performance of the overcurrent protection for the operation or protection team to assist in decision-making.

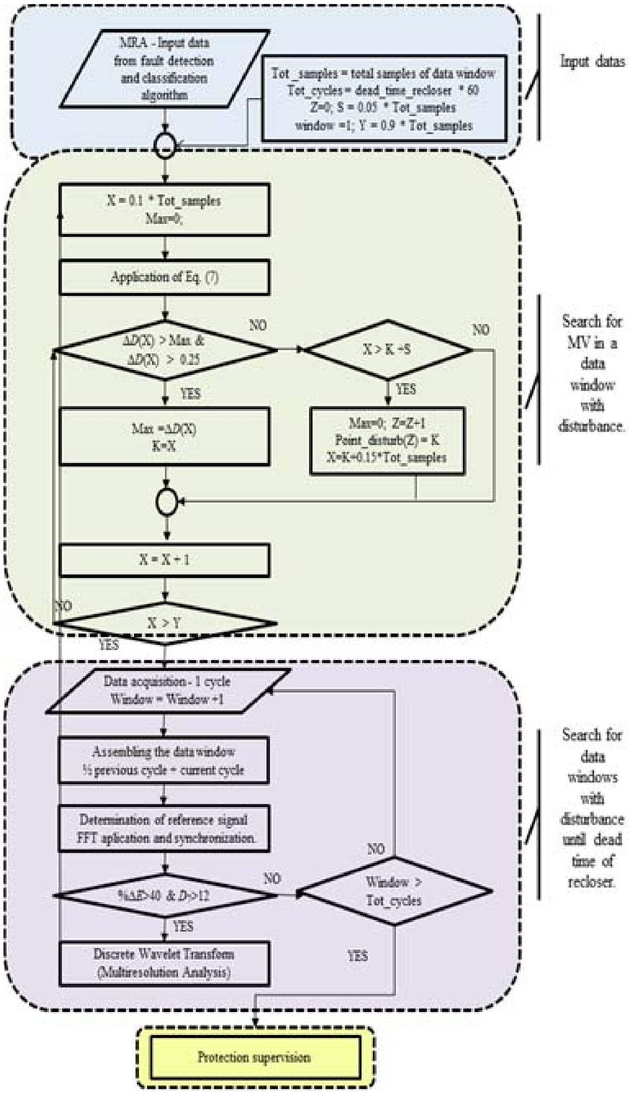

Fig. 12. Flowchart for overcurrent protect supervision.

The knowledge of protection system operation is obtained from the interaction with the heuristic rules used by an experienced protection team and a data base. The kind of protection coordination adopted, the number and the time between sudden changes identified from the beginning of short circuit are used as the data base. The knowledge base used is composed of a set of rules in the form of expertise knowledge from an elaborate analysis of the extracted features. These sets of rules are checked against a collection of facts or knowledge about the current situation. When the IF portion of a rule is satisfied by the facts, the action specified by the THEN portion is performed. It is shown below the set of rules considering the recloser-sectionalizer-fuse coordination (Fig. 13).

1. if NSC=1 then "the protection system did not work appropriately. The algorithm only detected the sudden changed caused by the short circuit" – detection: BSC.
2. if NSC = 2 & pos_FC ≈ pre_FC & ICD is false then "it is a transient fault or distribution transformer fuse operated: the protection system worked appropriately" – detection: BSC + ESC.
3. if NSC = 2 & pos_FC ≈ pre_FC and ICD is true then "it is an inrush current: if any distribution transformer fuse operated: the protection system did not work appropriately else the protection system worked appropriately" – detection: BSC + ESC.
4. if NSC = 2 & pos_FC ≈ 0 then "there was a failure in RFO"- detection: BSC + FOS.
5. if NSC=3 & pos_FC >> pre_FC then "it is a permanent fault and the protection system in first DOS did not work appropriately because the fault still exists"- detection: BSC + FOS+ RFO.
6. if NSC=3 & pos_FC ≈ pre_FC then "It is a transient fault eliminated in FOS and the protection system worked appropriately"- detection: BSC + FOS+ RFO.
7. if NSC=4 & pos_FC ≈ pre_FC then "it is a transient fault eliminated in RFO and the protection system worked appropriately"- detection: BSC + FOS+ RFO+ESC.
8. if NSC=4 & pos_FC ≈ 0 then "there was a failure in the first RDO"- detection: BSC + FOS+ RFO+DOS.
9. if NSC=5 & pos_FC ≈ pre_FC then "it is a transient fault eliminated in DOS and protection system worked appropriately"- detection: BSC+FOS+RFO+DOS+RDO.
10. if NSC=5 & pos_FC >> pre_FC then "it is a permanent fault and the protection system in first RDO did not work appropriately because the fault still exists"- detection: BSC + FOS+ RFO+DOS+RDO.
11. if NSC=6 & pos_FC < pre_FC and pos_FC > 0 then "it is a permanent fault and branch fuse operated: the protection system worked appropriately"- detection: BSC + FOS+ RFO+DOS+RDO+BF.
12. if NSC=6 & pos_FC ≈ 0 then "there was the fail in the second RDO"- detection: BSC + FOS+ RFO+DOS+RDO+ DOS.
13. if NSC=7 & pos_FC < pre_FC then "it is a permanent fault and the sectionalizer operated: the protection system worked appropriately"- detection: BSC + FOS+ RFO + DOS + RDO + DOS + SO + RDO.
14. if NSC=7 & pos_FC >> pre_FC then "it is a permanent fault and the recloser did not reach its dead time: protection system did not work appropriately because the fault still exists"- detection: BSC+FOS+ RFO+DOS+RDO+DOS+RDO.
15. if NSC=8 & pos_FC ≈ 0 then "it is a permanent fault and the protection system worked appropriately with the recloser reaching its dead time"- detection: BSC+FOS+ RFO+DOS+RDO+DOS+RDO+DTR.

16. if NSC $\geqslant$ 8 & pos_FC $>>$ 0 then “protection system did not work appropriately ” - detection: BSC+FOS+ RFO+DOS+RDO+DOS+RDO+?

Where BF: Branch Fuse Operation; BSC: Beginning of Short Circuit; DTR: Dead Time of Recloser; DOS: Delayed Opening Shot; ICD: Inrush Current Detection; ESC: Ending of Short Circuit; FOS: Fast Opening Shot; NSC: Number of Sudden Changes Detected; Pos_FC: Pos Fault Current; Pre_FC: Pre-Fault Current; RDO: Recloser Delayed Operating Shot; RFO: Recloser Fast Operating shot; SO: Sectionalizer Operation.

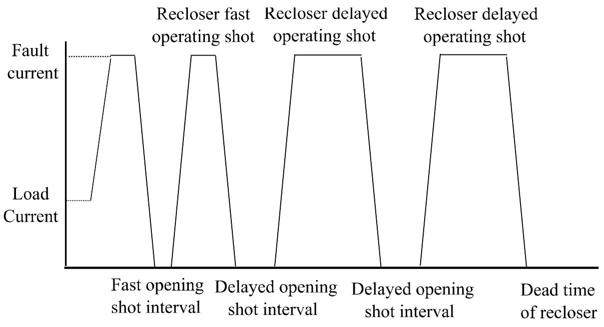

Fig. 13. Two fast and two delayed recloser operations.

III. APPLICATION

The proposed algorithm is implemented using Matlab on a 1GHz AMD Dual core personal computer. A 282-bus feeder whose line and load data are showed in [22] was selected to illustrate the performance of the algorithm. This system is derived from a distribution system from the southeast of Brazil. The line voltage in the substation is 13.8 kV. It was considered a load factor unitary and power factor 0.95 for all loads. 11 m - Poles and horizontal cross-arms (phase A |-- 0.6 m --| phase B |-- 1.2 m --| phase C) are used. The software Alternative Transient Program (ATP) was used to simulate in 30 buses randomly chosen (about 10% of the number of buses in the feeder) along the feeder, transient and permanent phase-to-ground short-circuit (AG, BG, CG), phase-to-phase short-circuit (AB, BC, CA), phase-to-phase-ground short-circuit (AB-G, BC-G, AC-G), three-phase short circuit and PQ problems. Although a probabilistic short-circuit has not been used, we believe that the number of simulations used (at least 300 simulations) were sufficient to evaluate the proposed algorithm. The fault resistance used was 10 Ω. Fig. 14 shows a transient three-phase short-circuit that is cleared during the fast recloser operation. Fig. 15 shows a permanent phase-to-phase short-circuit that is isolated by the operation of branch fuse. Fig. 16 shows a permanent phase-to-ground short-circuit that is isolated by the lockout of recloser. Fig. 17 shows a permanent phase-to-ground short-circuit for which the recloser-sectionalizer-fuse coordination does not work appropriately. All faults simulated were detected and classified satisfactorily by the algorithm. PQ problems were simulated and they were not detected by the algorithm. The evaluation of the protection system occurred after detection and the results were also satisfactory with the maximum error of the instant of detection of 0.01%. Table II shows the data recorded to faults shown in Figs. 14-17. Δti-variable represent the *i*-th interval between consecutive MVs. In recloser-sectionalizer-fuse coordination used in this simulation, there can be up to 7 intervals (8 MVs).

The algorithm detected 4 sudden changes in the transient three-phase short-circuit (Fig. 14) and post-fault current was around pre-fault current, therefore rule 7 was fired. The algorithm detected 6 sudden changes in the permanent phase-to-phase short-circuit (Fig. 15) and post-fault current was around pre-fault current, therefore the rule 11 was fired. The algorithm detected 8 sudden changes in the permanent phase-to-phase short-circuit (Fig. 16) and post-fault current was around zero, therefore the rule 15 was fired. The algorithm detected 5 sudden changes in the permanent phase-to-phase short-circuit (Fig. 17) and post-fault current was much larger than pre-fault current, therefore the rule 10 was fired.

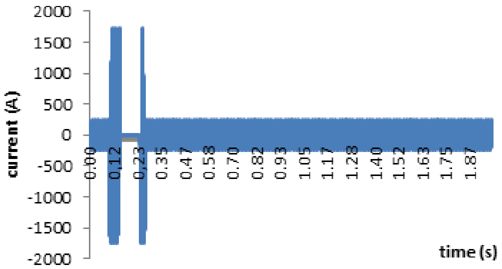

Fig. 14. A transient fault cleared during the fast recloser operation.

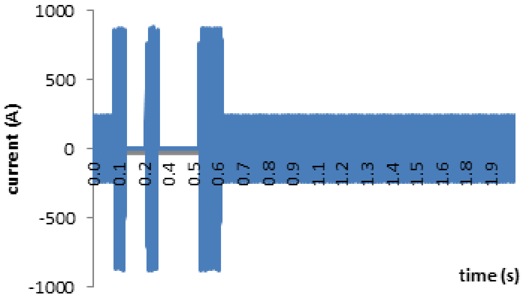

Fig. 15. A permanent fault isolated by branch fuse operation during the first recloser delayed operating shot.

IV. CONCLUSION

In this paper, an algorithm based on Discrete Wavelet Transform and a rule-based expert system is proposed to detect and classify faults and monitor the overcurrent protection system in radial distribution networks. Fault detection/classification and identification at the time of all sudden changes that occurred during the fault was performed with the MRA technique. The rule-based expert system was developed for evaluation of the overcurrent protection system during a fault. The significant characteristics of each routine were analyzed and discussed. This algorithm was tested on a real radial power distribution network using real data and Matlab software. It was able to detect single line to ground fault, phase to phase fault, double line to ground fault, and three phase fault and not to detect PQ problems. The system showed to be accurate in identifying the times of the protection system operation. The rule-based expert system analyzed correctly the protection system operation. The proposed algorithm has shown excellent results with a very low (few seconds) processing time, giving this tool great potential to assist in the operation during a fault, and supervise the protection system.

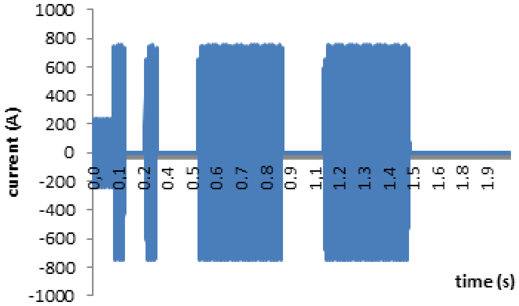

Fig. 16. A permanent fault isolated by lockout of recloser.

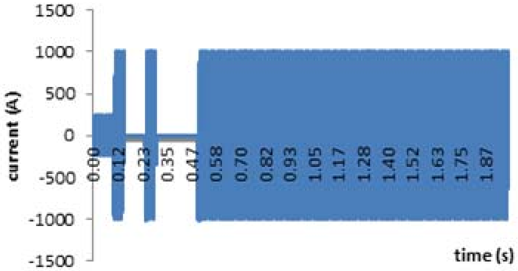

Fig. 17. A permanent fault that the recloser-sectionaliser-fuse coordination does not work appropriately.

TABLE II DATA BASE OBTAINED BY ALGORITHM AFTER SHORT CIRCUIT DETECTION.

	Fig. 14	**Fig. 15**	**Fig. 16**	**Fig. 17**
Date	12/04	15/04	17/04	20/04
Time	18:15	17:30	22:40	19:10
Rule fired	6	10	14	9
Duration time	Transient	Permanent	Permanent	Permanent
Δt_1 (ms)	50	50	50	50
Δt_2 (ms)	100	100	100	100
Δt_3 (ms)	20	50	50	50
Δt_4 (ms)		200	200	200
Δt_5 (ms)		100	400	
Δt_6 (ms)			200	
Δt_7 (ms)			400	

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