A Comparison of Transmission Line Fault Detection Methods

Y. M. P. Melo, F. V. Lopes, W. L. A. Neves, D. Fernandes Jr.

***Abstract*--Nowadays, the on-line monitoring of electric power systems has motivated several studies toward performing real-time implementations and evaluations of fault detection methods. The aim of this paper is to present details about real-time implementations of two digital fault detection methods and to evaluate their sensitivity to sources of errors commonly found in field applications such as variations in fault characteristics. Park's Transformation method (TDQ) and the Maximal Overlap Discrete Wavelet Transform (MODWT) method are evaluated here. Both methods were implemented in a Real Time Digital Simulator (RTDS™) to ensure that detections of faults were performed as quickly as possible. Evaluations for a 230 kV electric power system were performed assuming a transmission line with two monitored terminals. A total of 1650 fault cases were simulated. Three-phase current data taken at the transmission line terminals were used as inputs for each evaluated method. The fault detection of the both methods were not influenced by the fault characteristics, indicating the reliability of the methods.**

***Keywords*: Fault detection, RTDS™, transmission lines, Park Transform, Maximal Overlap Discrete Wavelet Transform.**

I. INTRODUCTION

TRANSMISSION lines need to operate properly and safely in order to ensure a continuous supply of electrical energy to the costumers, avoiding damage to the electric power system and equipment connected to it. However, transmission lines are at a great exposition to failures such as faults, voltage sags and switching transients, which should be detected quickly and efficiently, soon after the disturbance occurrence. By doing so, appropriate procedures can be taken to repair any problem.

Nowadays, the on-line monitoring of electric power systems has gained importance, what has motivated several studies toward performing real-time implementations and evaluations of fault detection methods. The aim of this paper is to present details about the real-time implementation of two digital fault detection methods, TDQ and MODWT, and to evaluate their sensitivity to sources of errors commonly found in field applications such as variations in fault characteristics.

The TDQ technique would produce no change in direct or quadrature axis for steady state operation, the DQ axes rotate at the power frequency in synchronism with the phase phasors of the three-phase system. However, in transient situations, the velocity of the current phasor with relation to the rotating reference is different from zero, which makes the generated signals have an oscillatory behavior.

The MODWT is a method based on the Discrete Wavelet Transform (DWT). DWT is a well-established transmission line fault detection method, which provides a non-uniform separation of frequencies present in the evaluated waveform signal.

Both evaluated methods were implemented in a Real Time Digital Simulator (RTDS™) to ensure that detections of faults were performed as quickly as possible. Maximal Overlap Discrete Wavelet Transform and TDQ methods were implemented using the Component Builder (CBuilder) tool available in the RTDS™ [1]. Then, other RTDS™ platforms, such as TLine, Draft and Run Time were used to simulate an electrical power system. Evaluations for a 230 kV electric power system were performed, considering a transmission line with two monitored terminals. A total of 1650 fault cases were simulated. In each case, fault resistance, fault location, fault inception angle and the fault type were varied. As inputs for each evaluated method, three-phase current data taken at both ends of the transmission line were used.

The paper contents are structured as follows: a brief description of the theory behind the two fault detection methods is presented in section II. Real time simulations and the analysis of results using both methods are described in section III. Finally, the main features of both methods are highlighted in the conclusions.

II. EVALUATED FAULT DETECTION METHODS

The mathematical formulation of the TDQ and MODWT techniques is presented next.

A. *Method I: Park Transform - TDQ*

Parks transformation is so called because it was developed by R. H. Park and his associates in the United States. This transform is also known as DQ transformation and was first proposed for the study of electrical machines, in which it was applied to transform three phase quantities of a stator in a fixed reference system on direct-axis and quadrature components in a rotating reference frame. In summary, one can say that TDQ decomposes armature quantities of a

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Y. M. P. de Melo is with Post-Graduate Program in Electrical Engineering - PPgEE - COPELE, University of Campina Grande (UFCG), 58429-900, Campina Grande - PB – Brazil (yonatha.melo@ee.ufcg.edu.br)
F. V. Lopes is with Electrical Engineering Department (ENE), University of Brasilia (UnB), Brasilia – Brazil (felipevlopes@unb.br)
W. L. A. Neves is with Electrical Engineering Department (DEE), Federal University of Campina Grande (UFCG), 58429-900, Campina Grande - PB – Brazil (waneves@dee.ufcg.edu.br)
D. Fernandes Jr is with Electrical Engineering Department (DEE), Federal University of Campina Grande (UFCG), 58429-900, Campina Grande - PB – Brazil (damasio@dee.ufcg.edu.br)

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synchronous rotating machine in two components: the direct-axis component, which is aligned with the axis of the field winding; and the quadrature component, which is in quadrature with this same axis [2]. TDQ technique would produce no change in direct or quadrature axis for steady state operation.

Here, the direct axis current is used to detect changes from normal operation. Faults should be detect as quickly as possible so the power supply is re-established. Park Transform stands out for its robustness among various fault detection techniques

Reference [3] proposes the use of a TDQ-based algorithm detect transients in transmission lines. DQ axes rotate at the power frequency in synchronism with the phase phasors of the three-phase system. During the steady state, in an ideal case, no frequency variations will be identified because the relative angular velocity between the mentioned phasor and the reference frame is zero. However, in transient situations, the relative velocity among the current phasor and the rotating reference is different from zero, which makes the generated signals have non-zero amplitudes and oscillatory behavior. Fig. 1 shows Park's Transformation Diagram.

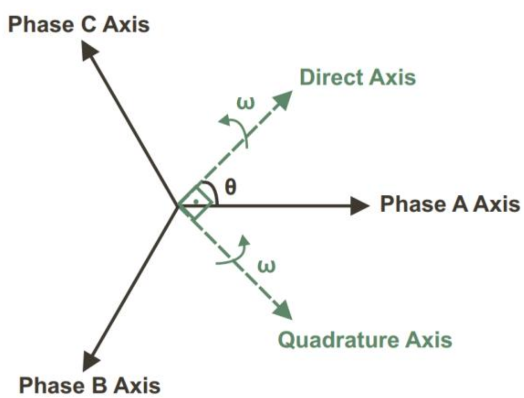

Fig. 1.Park's Transformation Diagram.

Input data used by the TDQ was the three-phase current. TDQ is performed next as shown in (1) and(2).

$$\begin{bmatrix} I_d(k) \\ Iq(k) \end{bmatrix} = P_{dq} \cdot \begin{bmatrix} I_a(k) \\ I_b(k) \\ I_c(k) \end{bmatrix}, \tag{1}$$

$$P_{dq} = \frac{2}{3} \cdot \begin{bmatrix} \cos(\phi) & \cos(\phi - 120°) & \cos(\phi + 120°) \\ -\sin(\phi) & -\sin(\phi - 120°) & -\sin(\phi + 120°) \end{bmatrix}, \tag{2}$$

where k is the k^{th} sample of current signal; I_a, I_b and I_c are the three-phase currents of the analyzed system; I_d and I_q are the direct and quadrature axis components, respectively; $\varphi = k\omega\Delta t + \theta$; ω is the angular frequency of the voltages and currents of the network; θ is the phase angle of the direct-axis current; and Δt is the sampling period of the analyzed signals.

Transients vary depending on certain fault characteristics. Thus, depending on the fault inception angle, the fault resistance, the power flow on the line, the fault location, among other factors, the system may have damped transient and frequency close to the network frequency. Thus, the initial instant of detection by the direct-axis transient coefficients (I_d) may be impaired because the fault can not be observed.

Reference [3] proposed the use of a more robust coefficient to detect the damped transients faults, as it can not predict the conditions under which a disturbance will occur. C_{dif} coefficient is used because it is more sensitive to the occurrence of high-frequency components and can be obtained using information from the present value $I_d(k)$ and its immediately preceding sample $I_d(k-1)$, as shown in (3).

$$C_{dif}(k) = G \cdot [I_d(k) - I_d(k-1)], \tag{3}$$

where G is the gain applied in the C_{dif} coefficient and equals to 1000.

To perform a more robust detection considering the presence of noise in the evaluated signals [3] proposes the use of the energy coefficient ξ_{dif} . It is computed by using a sliding rectangular window in time. N is the length of the rectangular window (equivalent to one cycle of the fundamental power frequency). The energy ξ_{dif} is computed as follows:

$$\xi_{dif}(n) = \sum_{k=n+1-N}^{n} C_{dif}(k)^2, \tag{4}$$

where $\xi_{dif}(n)$ is the n^{th} window energy.

Fig.2 shows the detection using energy coefficient $\xi_{dif}(k)$.

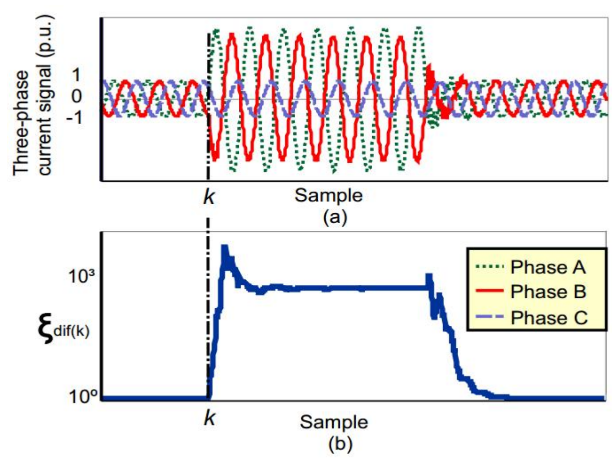

Fig. 2.Transients Detection using TDQ: (a) Three-phase current signal; (b) $\xi_{dif}(k)$ coefficient.

B. Method II: Maximal Overlap Discrete Wavelet Transform - MODWT

MODWT is an algorithm based on the Discrete Wavelet

Transform (DWT). DWT is a well-established transmission line fault detection method, which provides a non-uniform separation of frequencies in the evaluated waveform signal. For on-line applications the MODWT has advantages compared with the classical Discrete Wavelet Transform. In fact, MODWT detects fault-induced transients faster since it does not perform the downsampling process as the DWT does [4]. In this work MODWT is used and the Daubechies 4 (Db4) mother wavelet is chosen, which is widely known as the most suitable for power system applications [5].

Based on a multiresolution analysis, [6] proposes a fast and efficient algorithm for the calculation of DWT, which can be interpreted as a filter bank mathematically presented in (5) and (6).

$$c_1(k) = \sum_n g(n-2k)\cdot c_0(n), \tag{5}$$

$$d_1(k) = \sum_n h(n-2k)\cdot c_0(n), \tag{6}$$

where c_0 is the input data; c_1 and d_1 are the approximation and wavelet coefficients for the first scale, respectively; $g(k)$ and $h(k)$ are the low-pass and high-pass filters, respectively.

The information regarding the number of wavelet and approximation coefficients and both filters, as well as their values depend on the mother wavelet used. Using Db4 as the mother wavelet, one can obtain [7]:

$$g(1)=\frac{1+\sqrt{3}}{4\sqrt{2}};\quad g(2)=\frac{3+\sqrt{3}}{4\sqrt{2}};\quad g(3)=\frac{3-\sqrt{3}}{4\sqrt{2}};\quad g(4)=\frac{1-\sqrt{3}}{4\sqrt{2}} \tag{7}$$

Thus, mathematically, we will have:

$$h(1)=g(4);\quad h(2)=-g(3);\quad h(3)=g(2);\quad h(4)=-g(1) \tag{8}$$

By replacing (7) in (8), on can obtain:

$$h(1)=\frac{1-\sqrt{3}}{4\sqrt{2}};\quad h(2)=\frac{-3+\sqrt{3}}{4\sqrt{2}};\quad h(3)=\frac{3+\sqrt{3}}{4\sqrt{2}};\quad h(4)=\frac{-1-\sqrt{3}}{4\sqrt{2}} \tag{9}$$

MODWT is a variation of the classic wavelet and $\tilde{g}(l)$ and $\tilde{h}(l)$ are the MODWT's filters. MODWT filters can be obtained from the corresponding DWT filters as proposed by [8].

$$\tilde{g}(l) = g(l)/\sqrt{2} \tag{10}$$

$$\tilde{h}(l) = h(l)/\sqrt{2} \tag{11}$$

Therefore:

$$\tilde{h}(1)=\tilde{g}(4);\quad \tilde{h}(2)=-\tilde{g}(3);\quad \tilde{h}(3)=\tilde{g}(2);\quad \tilde{h}(4)=-\tilde{g}(1) \tag{12}$$

And then:

$$\tilde{g}(1)=\frac{1+\sqrt{3}}{8};\quad \tilde{g}(2)=\frac{3+\sqrt{3}}{8};\quad \tilde{g}(3)=\frac{3-\sqrt{3}}{8};\quad \tilde{g}(4)=\frac{1-\sqrt{3}}{8} \tag{13}$$

$$\tilde{h}(1)=\frac{1-\sqrt{3}}{8};\quad \tilde{h}(2)=\frac{-3+\sqrt{3}}{8};\quad \tilde{h}(3)=\frac{3+\sqrt{3}}{8};\quad \tilde{h}(4)=\frac{1-\sqrt{3}}{8} \tag{14}$$

Although approximation and wavelet coefficients appear in (15) and (16), only wavelet coefficients are used in the MODWT's analysis.

$$c_1(k) = \sum_{l=1}^{L} \tilde{g}(l)\cdot x(k+l-L) \tag{15}$$

$$d_1(k) = \sum_{l=1}^{L} \tilde{h}(l)\cdot x(k+l-L), \tag{16}$$

where L is the number of samples of the filters.

According to Parseval's theorem, the energy of the original signal x is equal to the sum of the energy of wavelet coefficients at different levels of resolution, $j = \{1; 2; ...; J\}$, with the energy of approximation coefficients at resolution level J, with $J \le J_{\max}$, [9]. This means that the signal energy can be partitioned in terms of wavelet coefficients of energy and approximation coefficients of energy of MODWT, as (17).

$$\sum_{k=1}^{k_t} |x(k)|^2 = \sum_{k=1}^{k_t} \left|c_J(k)\right|^2 + \sum_{j=1}^{J}\sum_{k=1}^{k_t} \left|d_j(k)\right|^2 \tag{17}$$

MODWT's wavelet coefficients at the first scale, are evaluated in real time, after obtaining a new wavelet coefficient as follows.

$$\xi(k) = \sum_{n=k+1-\Delta k}^{k} d_1^{\,2}(n) \tag{18}$$

which Δk is the number of samples/cycle.

Fig.3shows the procedures needed to calculate the energy coefficient.

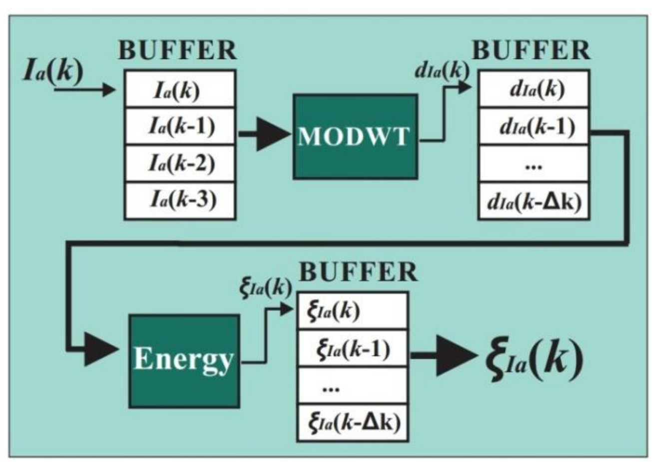

Fig. 3.Real-Time Energy of Wavelet Coefficient as proposed by [4] .

III. REAL-TIME SIMULATIONS

The power system analyzed consists of two generators, a 230 kV transmission line 225.9 km long, and two buses. The power frequency is 60Hz. Fig. 4 shows the electric power system.

Uncertainties due to protection schemes are ignored here, since the aim is to evaluate the performance of the two fault detection methods. The behavior of protection schemes due to other sources of uncertainties, as the current and voltage transformers were presented in [10] and [11].

Detailed specification of the various components of the system are provided in the Appendix.

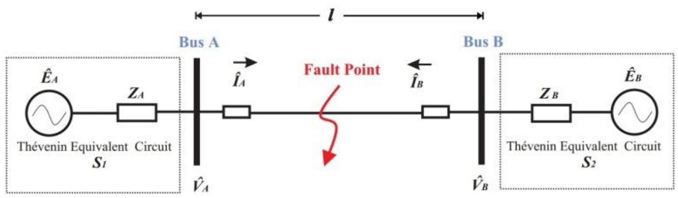

Fig. 4.Power system.

The transmission line was modeled in T-Line module of RSCAD as a fully transposed line using the distributed parameter line model. The electric power system was modeled on the Draft section of RSCAD and the fault detectors were implemented in CBuilder.

Basically, both algorithms for fault detection are divided into five parts: the current signals acquisition; the TDQ's and MODWT's application; the C_{dif} and wavelet coefficients computation; the energies computation; and, finally, the fault detection.

Detection of faults by both methods is significantly influenced by the adopted thresholds. Self-adaptive thresholds were used to ensure that the faults were detected even in situations of damped transients.

As TDQ uses the three phase current data simultaneously to compute the energies of the C_{dif}, only one flag per line terminals are necessary to indicate the fault condition. On the other hand, MODWT algorithm uses one flag to each current phase of each line terminal.

A number of 1650 cases of faults were analyzed in this paper, this cases were divided as shown in Table I.

TABLE I
FAULT CONDITIONS

Fault Resistance	0.1Ω; 1Ω; 3Ω; 10Ω; 90Ω
Fault Inception Angle	0°; 30°; 90°
Fault Location	10%; 15%; 20%; 30% 40%; 50%; 60%; 70%; 80%; 85%; 90%
Fault Type	AG; BG; CG; AB; AC; BC; ABG; ACG; BCG; ABC

The MODWT and TDQ methods are very reliable, regardless the fault type, the fault inception angle, the fault resistance and the fault location. Both methods detected 100% of the analyzed cases.

An important issue is the processing time needed to detect a fault. The mean processing times that each method need to detect faults in each transmission line terminal are shown in tables II to V.

The delays produced by traveling waves propagation on the transmission line were extracted. To calculate the propagation time of the traveling waves, the transmission line was considered lossless, then $v = 1/\sqrt{LC}$. Through this approach, the speed of wave propagation found was equal to nearly 98.3% of the light propagation speed.

TABLE II
DETECTION PROCESSING TIME AND STANDARD DEVIATION [NUMBER OF SAMPLES]
FAULT TYPE

Faults Types	Mean	
	TDQ	MODWT
AG	3.4521	3.3266
BG	3.4521	3.3368
CG	3.4521	3.3452
AB	3.4521	3.8818
AC	3.4521	3.8240
BC	3.4521	3.4672
ABG	3.4521	3.3149
ACG	3.4584	3.3290
BCG	3.4521	3.4962
ABC	3.4542	3.3833
Standard Deviation	0.0020	0.2111

TABLE III
DETECTION PROCESSING TIME AND STANDARD DEVIATION [NUMBER OF SAMPLES]
FAULT LOCATION

Faults Location [%]	Mean	
	TDQ	MODWT
10	3.6395	3.5979
15	3.4424	3.4473
20	3.2789	3.2946
30	3.4762	3.5771
40	3.5578	3.3751
50	3.1973	3.3490
60	3.5578	3.5485
70	3.4762	3.5031
80	3.2789	3.4459
85	3.4354	3.4421
90	3.6418	3.5953
Standard Deviation	0.1483	0.1035

Tables II, III and IV show that the performance of TDQ and MODWT are nearly the same. Here, the sampling period and integration step is 50 µs. Both methods have average processing times of less than 4 samples (0.2 ms).

The TDQ's and MODWT's methods had very similar results. Basically, TDQ presented a slightly faster detection and a standard deviation slightly lower than the MODWT, in most simulated cases. The mean value of the detection delay for the TDQ was 3.45 samples and for the MODWT's method was 3.47 samples.

TABLE IV
DETECTION PROCESSING TIME AND STANDARD DEVIATION [NUMBER OF SAMPLES]
FAULT RESISTANCE

Fault Resistance [Ω]	Mean	
	TDQ	MODWT
0.1	3.4537	3.4536
1	3.4537	3.4470
3	3.4521	3.4129
10	3.4521	3.5063
90	3.4531	3.5325
Standard Deviation	0.00073	0.04820

TABLE V
DETECTION PROCESSING TIME AND STANDARD DEVIATION [NUMBER OF SAMPLES]
FAULT INCEPTION ANGLE

Fault Inception Angle[°]	Mean	
	TDQ	MODWT
0	3.4523	3.4651
30	3.4542	3.4468
90	3.4523	3.4996
Standard Deviation	0.0011	0.0268

As previously mentioned, all the cases were detected correctly. However, further investigation is needed to pinpoint situations where the methods fail. The literature shows that a not so good starting value for the threshold calibration may result in undue detections in their first iterations even during normal system operation, [4].

IV. CONCLUSIONS

This paper showed a comparison of two methods for the detection of faults in transmission lines. The first one was the TDQ, which analyzed all three phase phasors simultaneously. The second method was the MODWT, that is an algorithm based on the classical DWT. Both methods have been implemented in real time using the CBuilder of the RTDS^{TM}.

The results of both methods were reliable because 100% of the simulated cases were detected. Results shows that the performance of both methods are nearly the same. The method based on the TDQ presents, in most simulated cases, slightly faster detection than MODWT, when using self-adaptive thresholds based on energy coefficients for both methods. The threshold values are very important parameter for the correct and fast detection.

The TDQ presents some advantages when compared with the MODWT, as the simpler implementation and the possibility of the simultaneously analysis of the three-phase system just evaluating one variable.

V. APPENDIX

Detailed specification of the generators and the transmission line are presented as follows.

TABLE VI
GENERATORS DATA - 230 KV

Generator A	1.0237 (p.u.)	0°
Generator B	1.0237 (p.u.)	-8°

TABLE VII
GENERATORS DATA - IMPEDANCES [Ω/km]

Generator A	R_0=0.6538	R_1=1.4260	X_0=9.2342	X_1=12.4850
Generator B	R_0=4.5018	R_1=5.3471	X_0=34.9960	X_1=31,7160

TABLE VIII
TRANSMISSION LINE DATA - 230 KV/60 HZ

Sequence	R (Ω/km)	X (Ω/km)	ωC(μmho/km)
Zero	0.4111	1.3723	2.490
Positive	0.0975	0.5199	3.144

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