Fault Induced Transient Detection in Power Systems: An Adaptive Approach Considering Noisy Environment

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***Abstract*-- This paper proposes a new approach for transients detection, specifically for faults-induced transients of common and high impedance faults. The approach is based on the DQ-transformation with an adaptive filtering technique in order to generate a detection signal. Transients detection is made by means of a mathematical algorithm which is self-adaptive to the noise level of the detection signal. The proposed algorithm is based on the analysis of two dynamic thresholds. The thresholds definition is made with an accumulating confidence decision formulation in order to verify true detections. The proposed approach is evaluated using simulated cases of high impedance faults on a model of a real distribution system. Comparisons with the last published method based on DQ-transformation show that the proposed approach is more robust to noise.**

***Keywords*: Transients detection, DQ-transformation, Adaptive Filter, Power Systems, Faults.**

I. INTRODUCTION

Detection of disturbances in electrical power systems is of fundamental importance for protection and diagnosis purposes. In particular, faults detection is of major importance in order to mitigate their economical and safety impact. Disturbances as faults generate transient in voltage and current signals. Fault detection can be exploited in several ways, for example, to initiate signals recording, a protection action or an event diagnosis. A robust detection method must be able to detect both high and low energy events, like those produced by High Impedance Faults (HIF) in distribution systems [1]. This type of fault show very smooth features including low energy transients that can easily be mixed up with noise. In this context, transients must be discriminated from normal noise levels superimposed on the monitored signals.

There are several works available in literature that deal with the issue of transients detection using analog [2]- [3] or digital implementations [4]-[9]. Taking into account the concept exposed in [4], transients detection methods mainly work in two steps: a transformation step that generates some set of detection signal, where the disturbance becomes easiest to discriminate; an Accumulating Confidence Decision algorithm (ACD) that ensures the correct transient identification by means of some set of thresholds and accumulators. In this context, an efficient detection approach must complement an effective transformation with an effective ACD.

The sample-by-sample and cycle-by-cycle differences of digital signals are the simplest ways to construct a detection signal. However, the principal drawback is that transients at any frequency band are treated in the same way. A more efficient approach is the difference between the output of a median and a mean filter [4]. There also exists others concepts that gained recently great popularity, as the Details of the Discrete Wavelet Transform (DWT) for detection signals construction. Reference [5] uses a moving absolute-value summation filter applied on the first detail of a DWT of phase currents. With the use of predefined thresholds, HIF can be detected and classified. In [6] is proposed a similar approach but using the residual voltage signal to detect transients due HIF in unearthed distribution systems. The energy of first details of DWT of phase currents are used as detection signals in [7]. Then, with some developed rules, single and multiple disturbances are detected and classified from oscilographic records.

Another interesting way to generate a detection signal is using the Park's transformation, idea proposed in [8] for two-terminal based travelling wave fault location. The principal advantage of Park's transformation is the capability to generate a unique detection signal that represents all three phases. Many types of transients can be detected using Park's transformation approach [9].

Independently of what detection signal is used, all ACD algorithms are based on fixed thresholds that require a previous study of the system noise levels. Although certain tuning of the ACD by the user is inevitable, the present work aims to simplify this task. In order to assess the three-phase

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power system signal by means of only one, the detection signal is based on the DQ-Transformation (DQT). An ACD algorithm is proposed and it is self-adaptive with the noise level of the signal, using maximum and minimum values located in past samples of the detection signal. As digital measurement units are widely used to monitor actual power systems, the present work is focused on a digital implementation. This work is also concerned on the pure detection task: if it is correctly performed, a classification method can be used in order to classify the event

The remaining of this paper is organized as follows: A general description of the proposed method is presented in section II followed by the mathematical background of its contents. Section III evaluates the proposed method using simulated test cases of HIF applied on a model of a real distribution system. The approach is also compared with the method presented in [8]. Final comments and conclusions of the work are presented in section IV.

II. Proposed Approach

The proposed approach is summarized in Fig. 1. It consists of a transformation block to generate the detection signal ($d[n]$) and the ACD block to perform transient detection. The transformation block firstly applies the DQT to the three-phase signal set and the direct signal ($v_d[n]$) is filtered in order to improve its characteristics for detection. Finally, the detection signal feeds the ACD block in order to detect transients and store them in the vector $T_d[k]$. Each block that composes the overall algorithm are explained and detailed in the next subsections.

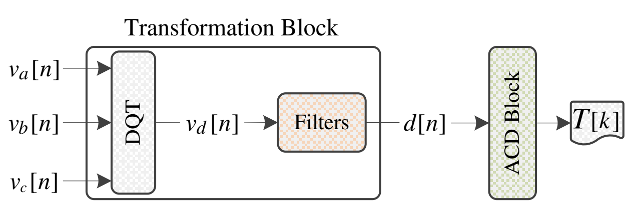

Fig. 1. General proposed approach for transients detection.

A. DQ-transformation

The most known application of the DQT is on analysis of rotating electric machines, transforming variable stator inductances in constant inductances on a rotating reference frame with synchronous speed [10]. Here, this concept is applied to a set of three signals denominated as three-phase signal. Continuous time is considered here for purposes of generalization, but the method is finally implemented in discrete time.

Considering some time instant t, the DQT can be expressed in matrix form as:

$$\begin{bmatrix} v_d(t) \\ v_q(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\phi_p(t)) & \cos\left(\phi_p(t)-\frac{2\pi}{3}\right) & \cos\left(\phi_p(t)+\frac{2\pi}{3}\right) \\ -\sin(\phi_p(t)) & -\sin\left(\phi_p(t)-\frac{2\pi}{3}\right) & -\sin\left(\phi_p(t)+\frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} \quad (1)$$

where $v_a(t)$, $v_b(t)$, and $v_c(t)$, are the monitored signals of the phases a, b, c and $v_d(t)$ and $v_q(t)$, are the components of direct and quadrature axis. Equation (1) defines a change in the reference frame of the three-phase signal that is rotating with an arbitrary time-dependent phase defined as $\phi_p(t)$. In this work, this phase is considered a linear function:

$$\phi_p(t) = \omega_p t + \theta_p, \quad (2)$$

where ω_p is a constant angular velocity in rad/s and θ_p is the initial angle of the reference frame when t = 0 and has a random value.

With respect to the DQT, $v_d(t)$ and $v_q(t)$ can form a complex signal defined as:

$$v_{dq}(t) = v_d(t) + j\,v_q(t), \quad (3)$$

which can be written in polar form as:

$$v_{dq}(t) = m(t)\,e^{j\varphi(t)}\,e^{j\phi_p(t)}, \quad (4)$$

where

$$m(t) = \sqrt{m_1^2(t) + m_2^2(t)}, \quad (5)$$

$$m_1(t) = \sqrt{\frac{2}{3}}\left(v_a(t) - \frac{1}{2}v_b(t) - \frac{1}{2}v_c(t)\right), \quad (6)$$

$$m_2(t) = \sqrt{\frac{2}{3}}\,\frac{\sqrt{3}}{2}\left(v_b(t) - v_c(t)\right), \quad (7)$$

$$\varphi(t) = \arg\left(m_1(t) + j\,m_2(t)\right). \quad (8)$$

Defining:

$$M(t) = m(t)\,e^{j\varphi(t)} \quad (9)$$

and replacing (9) in (4)

$$v_{dq}(t) = M(t)\,e^{j\phi_p(t)}. \quad (10)$$

Equation (10) means that DQT performs a modulation of the complex signal $M(t)$ by the function $\exp(j\phi_p(t))$. Considering (2), DQT makes a shift of the frequency spectrum to the negative part by a quantity of ω_p. The real and imaginary parts of the signal $M(t)$ defined in (9) are just the α and β components of the αβ-transformation, widely used in power system analysis [11]. Hence, when (10) is applied on any three-phase signal from power systems (voltages in this work), one could state:

- $v_d(t)$and $v_q(t)$ are constants if $\{v_a(t), v_b(t), v_c(t)\}$ is balanced, without harmonics or transients;
- a second harmonic component appears superimposed on $v_d(t)$ and $v_q(t)$, if $\{v_a(t), v_b(t), v_c(t)\}$ are unbalanced;
- if some harmonic exists on the set $\{v_a(t), v_b(t), v_c(t)\}$, $v_d(t)$ and $v_q(t)$ present the same harmonic shifted by ω_p, the same happens with the frequency spectrum of transients components;
- balanced thirds harmonics in $\{v_a(t), v_b(t), v_c(t)\}$ are canceled by the DQT and they have no effect on $v_d(t)$ and v_q-(t).

The first of above characteristic is the main reason to use the DQT as a filtering technique, allowing transforming the fundamental frequency component in a dc-offset.

B. Filters

From this section the signals will be considered as discrete time sequences. However, the analysis presented in section A is still valid. In general form, the signal $v_d[n]$ can be composed by a dc-offset with superimposed harmonics of the fundamental frequency, specially the second harmonic due to the unbalance in the three-phase signal. The purpose of filtering the $v_d[n]$ is to attenuate these harmonics letting only noise and transients components pass. In this work is proposed the use of an adaptive filter technique; however other filters can be designed to attenuate these harmonics. Many applications of adaptive filters have been described in literature [12]. As harmonics have a narrow bands frequency spectrum, the adaptive filter is implemented as a narrowband interference suppressor, which is shown in Fig. 2. Finite Impulse Response (FIR) type adaptive filter is by far the most practical and widely used because it has only adjustable zeros and stabilities problems only concerns the adjustment coefficients. The least-mean-square (LMS) algorithm is the basic manner to adaptively adjust the coefficients of a FIR filter and its implementation is well described in [12].

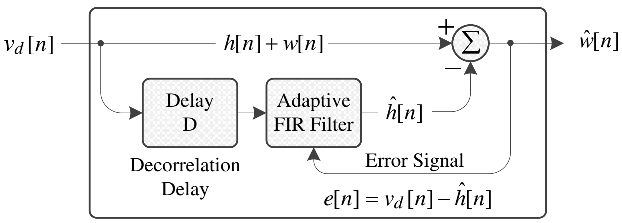

Fig. 2. Adaptive filter for estimating and suppressing a narrowband interference [12].

The narrowband signal (harmonics) of $v_d[n]$ is defined as $h[n]$ and the wide band signal (noise plus transients) as $w[n]$. The delay block is chosen sufficiently large so that the wideband signal components $w[n]$ and $w[n\text{-}D]$ are uncorrelated. Then, the adaptive filter estimates $h[n]$ and then an estimated version of $w[n]$ can be separated from the original signal. In theory, the estimated signal $\hat{w}[n]$ is composed only by noise and transients and this signal is used as the detection signal:

$$d[n]=\hat{w}[n]. \tag{11}$$

C. Accumulating Confidence Decision Block

After the filtering stage, it is assumed that $d[n]$ is composed mainly by white noise and a transient term with attenuated harmonics. If noise is not present in the signal, a detection algorithm would be easy to implement because any non-common value would be a transient. As noise is inevitable in any real-life signal, the detection algorithm must be able to deal with it. This task is generally done by some fixed threshold and a kind of accumulated confidence decision algorithm [4]. The problems associated with a fixed threshold are that: a previous study must be perform to define the normal noise level on the measured signals; if normal noise level changes, the threshold may not perform as it should. Then, the definition of a threshold is of fundamental importance in order to develop a reliable detection algorithm. The basic idea in this work is to define a self-adaptive threshold that automatically gets adapted to noise levels.

The proposed ACD block is composed by an algorithm that defines thresholds in function of the maximum and minimum values in a window of past samples of $d[n]$. The proposed algorithm is best explained by the flowchart shown in Fig. 3.

The algorithm begins with the definition of the initialization data. As can be seen from Fig. 3, it is not possible to detect any transient in the first $Ns+Ds$ samples because the algorithm is being initialized. When this process finishes, two thresholds are defined as the maximum and minimum values in the window of length Ns that lags Ds samples from the actual sample n. This threshold is also adjusted by the tolerance η. Each time in which the actual sample in $d[n]$ gets out the band defined by the thresholds the variable c is incremented by 1 and the thresholds stays frozen. Meanwhile, each step on the sequence $d[n]$ increments the variable t by 1. If c reaches T_C before t reaches $T\tau$, the transient is detected and the threshold calculation is restarted. Then, the algorithm is unable to detect other transients in a time $Ns+Ds$. On the other hand, if t reaches $T\tau$ before c reaches T_C the detected event is understood as a spurious signal or a change in noise level, and nothing is detected.

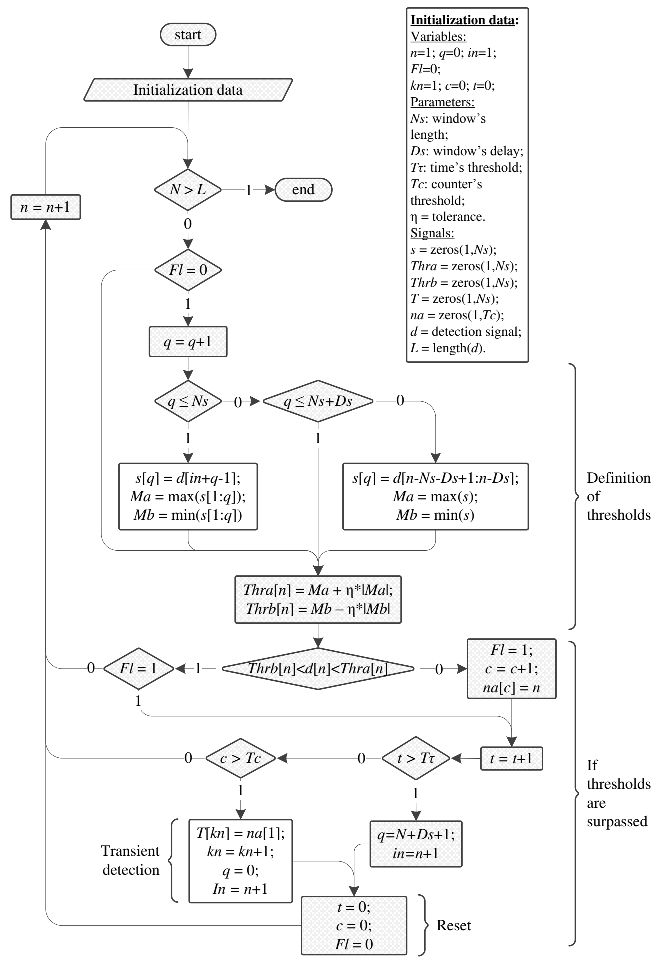

Fig. 3. Logic block: accumulating confidence decision algorithm.

III. Evaluation of the Algorithm

Medium voltage distribution networks are generally exposed to leaning trees or incidents where conductors get broken, events that have a great probability to produce HIF [1]. This fault type generates low currents with a particular harmonic content, and low energy transients, as demonstrated in works as [13], [6]. Therefore, simulations of HIF in a distribution networks can be considered as the worst scenario to evaluate a transient detection algorithm. In this context, a real distribution system was modeled and three HIF were simulated in order to exemplify the proposed transient detection algorithm.

The method for transient detection proposed in [8] was implemented in order to have a reference point for the analysis. This approach was conceived to detect arrivals of fault generated travelling waves and perform the two terminal fault location method. It can be considered as the most recent publication that use the DQT as a basis to perform transient detection. The algorithm proposed in the present work is referred as the Method 1 (M1) and the algorithm presented in [8] is referred as the Method 2 (M2). The two approaches are evaluated with and without consideration of a noisy environment.

A. Modeling and Simulations

A real distribution network was modeled using the Alternative Transient Program (ATP) [14] in order to evaluate the algorithms M1 and M2. This network is located at south of Brazil and belongs to the CELESC S.A. Company. Fig. 4 shows a line diagram of the distribution system, which is composed by an urban area clearly separated from a rural area by means of a recloser. Three-phase lines mostly compounds the urban area meanwhile single-phase lines compounds the rural area. CELESC SA. has a georeferenced database of its distribution systems that are constituted of a large amount of information. As a manual written of the ATP card file would be very difficult, a program was conceived in Matlab® in order to automatically generate the ATP card file from the datasheets.

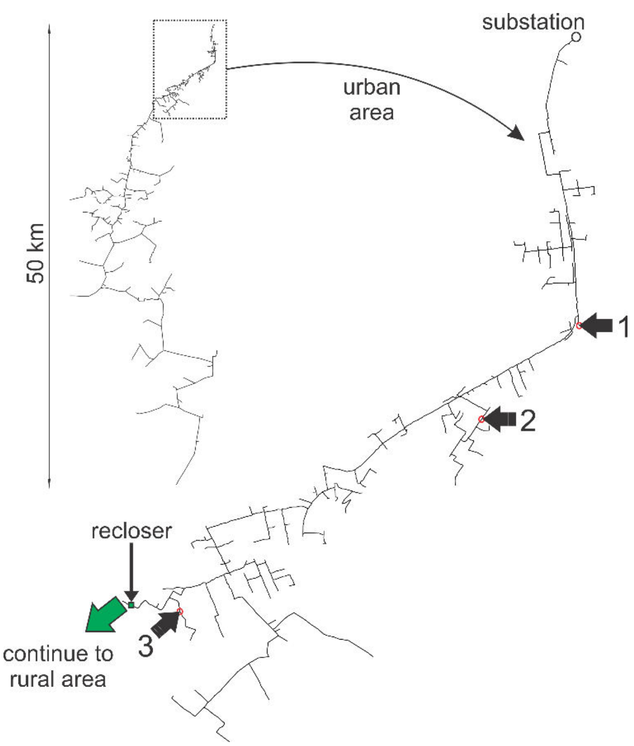

Fig. 4. Line diagram of the test distribution network.

Three HIF were simulated in the urban area. These faults are indicated in the Fig. 4 with black arrows numbered as 1, 2 and 3. The HIF were modeled by the proposal presented in [13] and its parameters were tuned in order to have fault currents around 5% of the actual load current with a third harmonic content of 4% of the fault current fundamental component.

B. Comparative Analysis

This subsection presents the performance of the proposed transient detection method (M1), compared with that proposed in [8] (M2) using simulated cases. Results are presented in figures to illustrate the progression of the detection signals and thresholds. Fig. 5 shows the detection signal with the thresholds for the three simulated cases using the M1. In this example the signals are ideals, without consideration of noise. There can be seen that the detection signal still has an attenuated second harmonic component, but the M1 continues to work.

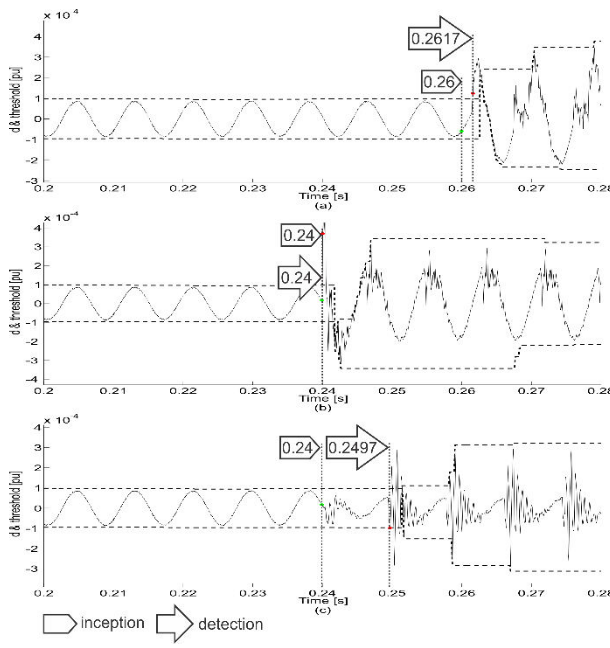

Fig. 5. Detection signal and thresholds of the M1 without noise: (a) fault in phase B at point 1; (b) fault in phase A at point 2; (c) fault in phase C at point 3.

Fig. 6 shows the detection signal and the threshold with the parameters adjustment recommended in [8]. The detection signal surpasses the threshold by a considerable amount and transient detection instant is closer to the real fault inception instant. In an environment without presence of noise, M1 and M2 works for which they were designed.

Now, Fig. 7 presents the same evaluation presented in Fig. 5 but with the presence of an additive noise, which Signal to Noise Ratio (SNR) is about 60 dB. Fig. 7 shows that the M1 still works with efficiency. Fig. 8 presents the detection signal and threshold for the M2 considering the same levels of noise, but only for the fault at the point 1. In contrast, the detection signal seems to be unchanged at the fault inception instant and the recommended threshold is always located above the detection signal. M2 does not work in this case with the parameters adjustment recommended by [8].

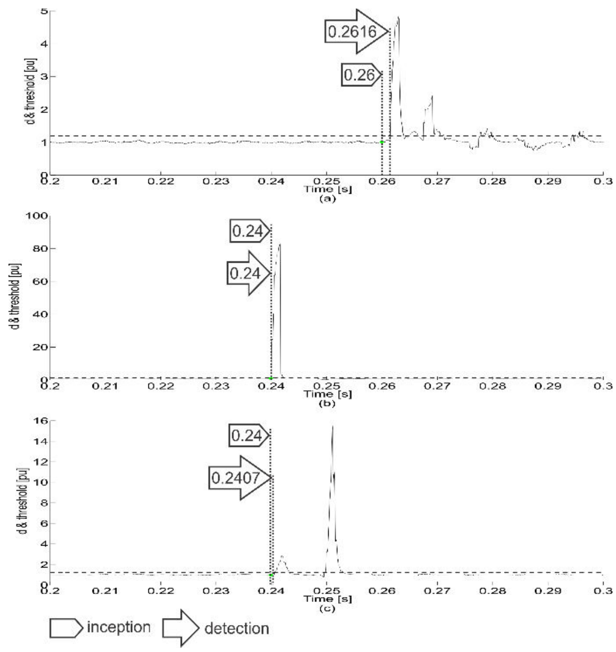

Fig. 6. Detection signal and thresholds of the M2 without noise: (a) fault in phase B at point 1; (b) fault in phase A at point 2; (c) fault in phase C at point 3.

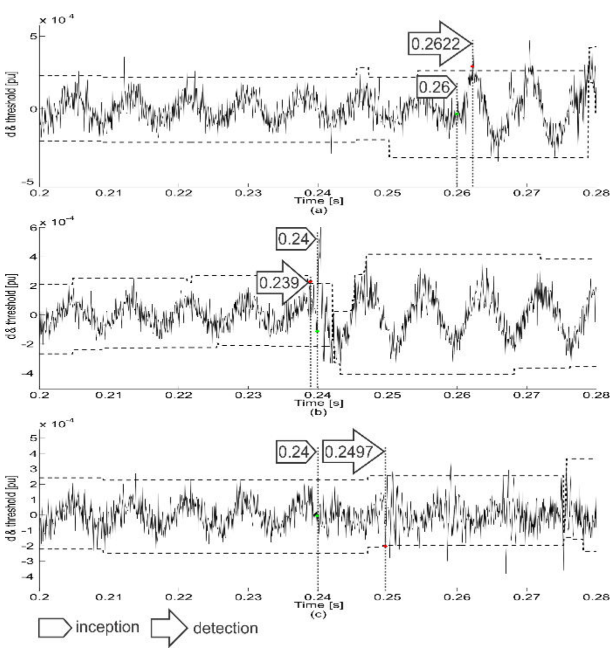

Fig. 7. Detection signal and thresholds of the M1 with SNR equal to60 dB: (a) fault in phase B at point 1; (b) fault in phase A at point 2; (c) fault in phase C at point 3.

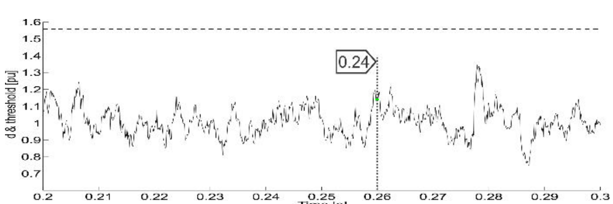

Fig. 8. Detection signal and thresholds of the M2 with SNR equal to 60 dB: fault in phase B at point 1.

Results shown in this section demonstrate that the detection signal of the M1 presents a better behavior than the detection signal of the M2 with the consideration of noise. It is: the detection signal of the M1 presents a perceptible change when the fault is induced but the detection signal of the M2 does not. The M1 uses two thresholds permitting to detect transients that behave with positive or negative spikes. On the other hand, the M2 has a unique threshold that must be previously fixed. The M2 shows to be more accurate than the M1 if noise is not present in the three-phase signal, but the M2 is not able to perform transient detection if a great SNR exists, contrary to the M1. The results are summarized in Table I, where the cases 1, 2 and 3 refer to the Fig. 5-8.

TABLE I
SUMMARY OF RESULTS

Case	Fault Inception	Fault Detection			
		without noise		with noise	
		M1	M2	M1	M2
1	0.26 s	0.2617 s	0.2616 s	0.2622 s	-
2	0.24 s	0.2400 s	0.2400 s	0.2390 s	-
3	0.24 s	0.2497 s	0.2407 s	0.2497 s	-

IV. CONCLUSIONS

Detection of transients on power system signals is of great importance for protection and diagnosis of the power network. Voltage transients can be caused by faults or normal power system operation and are specially causes of complaints from customers. For this reason, utilities are focusing their attention on develop techniques capable to detect transients in an efficient way. As noise is unavoidable in real-life applications, any transient detection technique must be able to discriminate the true transient from noise.

In this paper, an algorithm that assess three-phase signal using only one signal was proposed. This task was made using the direct axis signal from the DQT. An adaptive filter scheme was proposed in order to attenuate the harmonic content of the detection signal because these components are unnecessary for the proposed transient detection approach. Finally, an ACD algorithm was proposed that generates a set of two self-adapting thresholds based on maximum and minimum values of the detection signal. The proposed approach was tested with simulations of a real distribution system. Results shows that the proposed algorithm is able to detect the fault induced transients inclusive with the presence of noise.

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