HIGH IMPEDANCE FAULT DETECTION IN DISTRIBUTION SYSTEMS: ADAPTIVE APPROACH CONSIDERING NOISING ENVIRONMENT

Renato FERRAZ	Leonardo IURINIC	Arturo BRETAS
UFRGS – Brazil	UFRGS – Brazil	UFRGS - Brazil
rferraz@ece.ufrgs.br	uiurinic@ece.ufrgs.br	abretas@ece.ufrgs.br
Arlan BETTIOL	Antônio CARNIATO	Luis PASSOS
NEO DOMINO – Brazil	NEO DOMINO – Brazil	NEO DOMINO – Brazil
arlan@neodomino.com.br	carniato@neodomino.com.br	luis@neodomino.com.br
Igor KHAIRALLA	Rafael HOMMA	Adriano BAADER
CELESC SA. – Brazil	CELESC SA. – Brazil	CELESC SA. – Brazil
igorkk@celesc.com.br	rafaelzh@celesc.com.br	adrianob@celesc.com.br

ABSTRACT

This paper proposes a new approach for high impedance faults detection. The approach is based on the DQ-transformation with an adaptive filtering technique for detection signal generation. Transient signals detection is made by means of two thresholds, which are self-adaptive with the noise level present on the detection signal. The thresholds definition is made with an algorithm designed to confirm true transients from false. The proposed approach is evaluated through simulated test scenarios of high impedance faults on a modelled real distribution network. An evaluation of the proposal with additive noise confirms the robustness in detection of transients induced by high impedance faults.

INTRODUCTION

Distribution systems operation, control and protection are usually done using three-phase voltages and current signals measured in the substation and other system nodes. Any disturbance, as a fault, generates transients in voltages and current signals due to a fast system state change. Common faults can generate transients followed by a substantial change in voltage and current magnitudes. By contrast, High Impedance Faults (HIF) shows very smooth features including low energy transients and harmonics, which can be easily mixed up with noise [1]. As a consequence, HIF are very difficult to be detected, and as a result, no diagnosis and protection action can be performed. Thus this fault type can be dangerous for any living beings, since the system is still energized. In this context, HIF detection is a very important topic to be studied.

In order to detect a disturbance, currently state-of-the art methods are usually composed of two principal procedures: A transformation step and an Accumulating Confidence Decision algorithm (ACD) for detection and classification [2]. The first consists in the generation of detection signals, where the transient becomes easier to discriminate, as for example, a derivative filter. The second consists on variations of decision algorithms, which ensure the correct disturbance identification. In this framework, many studies are available in literature performing the task with analog [3], [4] or digital implementations [2], [5]-[8].

Currently, several works have been proposed in order to generate detection signals on three-phase voltages or currents. These proposed approaches vary from simple formulations based on a sample-by-sample or the cycle-by-cycle difference, to more complex formulations with the use arrays of filters or some detail of a Discrete Wavelet Transform (DFT) [5] [6] [7]. Another novel way to generate a detection signal is using the Park's transformation, idea proposed in [8] for two-terminal travelling wave fault location method. The principal advantage of Park's transformation is the capability to generate a unique detection signal that represent all three phases. Many types of transient can be detected using Park's transformation approach [9].

Before generating the detection signal, all approaches require the definition of some thresholds that can be obtained by analyzing a large data base of known events, or by means of some self-adaptive rule based on characteristics extracted of the analyzed signals.

A not yet investigated problem in the mentioned approaches is the effect of the natural noise present in signals, and how to deal with this issue. In order to realize a complete and robust detection method, the present work proposes to use the DQ-transformation (DQT) with an adaptive FIR filter to construct a detection signal and then an ACD algorithm is proposed whose is self-adaptive with the noise level of the signal. In order to investigate the formulation performance, a real distribution system was modeled using the Alternative Transient Program (ATP) and HIFs were simulated in different critical points of this modeled system. 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: The description of the proposed method is presented in section II. Section III evaluate the proposed method using simulations of HIF. Final comments and conclusions are presented in section IV.

PROPOSED APPROACH

The proposed approach is presented in the 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 fids the ACD block in order to detect transients and store them in the vector $T_d[k]$. Each block that composes the overall algorithm is explained and detailed in the next subsections.

The DQT Block

The most known application of the DQT is in 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.

In order to explicit important properties of 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:

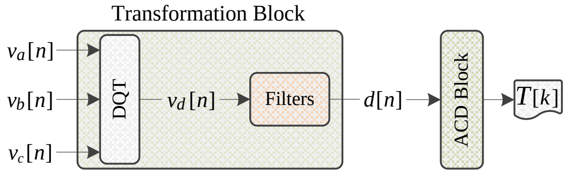

Fig. 1. Generalized schem of the proposed approach for HIF-induced transients detection.

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

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 case), it is possible to pointwise the next particular cases:

- $v_d(t)$and $v_q(t)$ are constants if $\{v_a(t), v_b(t), v_c(t)\}$ is balanced, without harmonics nor transients;
- a second harmonic component appear superimposed on $v_d(t)$ and $v_q(t)$, if $\{v_a(t), v_b(t), v_c(t)\}$ are unbalanced;
- if some harmonic exist 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 not 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, permitting to transform the fundamental frequency component in a dc-offset.

The Filter Block

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. Here is proposed the use of an adaptive filter technique, but others filters can be designed to attenuate the 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 to coefficients adjustment. 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].

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:

$$d[n] = \hat{w}[n]. \qquad (11)$$

The Accumulating Confidence Algorithm Block

After filtering stage, it is assumed that $d[n]$ is composed principally by white noise and a transient term with attenuated harmonics. If noise not is 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 [2]. 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 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

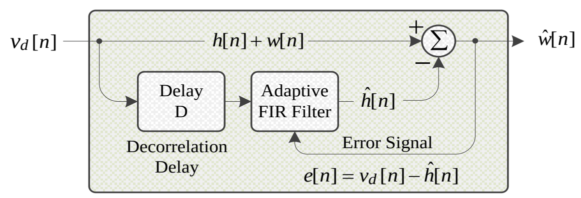

Fig. 2. Adaptive filter as a narrowband interference suppressor

flowchart shown in

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

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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 stay frozen. Meanwhile, each step on the sequence $d[n]$ increments the variable t by 1. If c reaches Tc 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 Tc the detected event is understood as a spurious signal or a change in noise level, and nothing is detected.

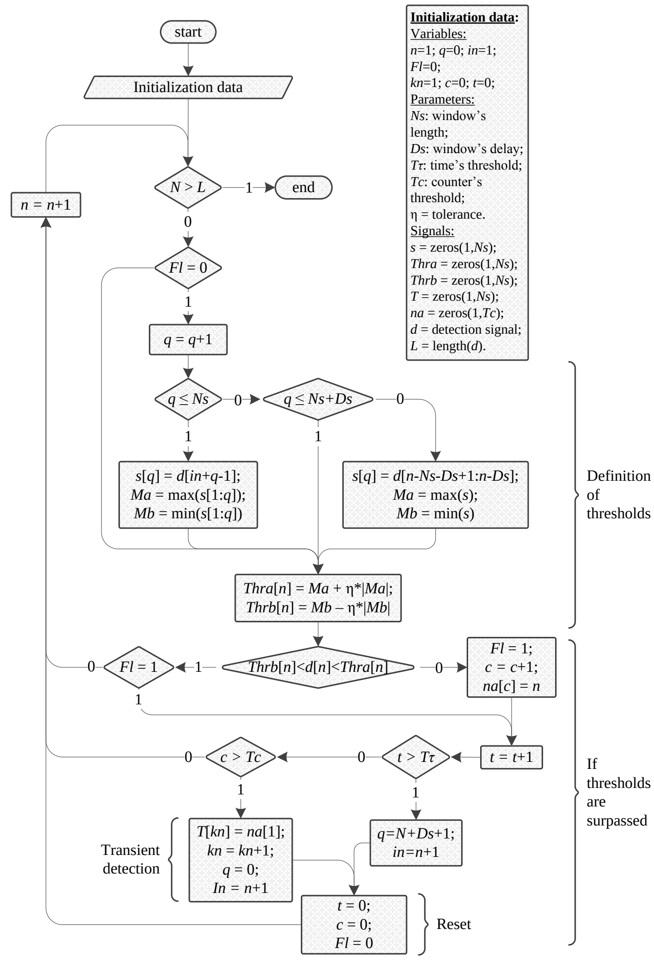

Fig. 3. Logic block: accumulating confidence decision algorithm.

EVALUATION OF THE PROPOSED ALGORITHM

Medium voltage distribution networks are generally exposed to leaning trees or incidents where conductors get rotten, 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]. In this context, a real distribution system was modeled and ten HIF were simulated in different critical points of the modeled system in order to exemplify the proposed algorithm.

Modeling of the distribution network and HIF

A real distribution network was modeled using the Alternative Transient Program (ATP) [14] in order to evaluate the proposed algorithm. This network is located at south of Brazil and belongs to the CELESC SA. company. The 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 compose urban areas meanwhile single-phase lines compose 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.

Ten HIF were simulated, five in the urban area and five in the rural area. These faults are indicated in the Fig. 4 with black arrows numbered from 1 to 10. 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. For faults simulated in the urban area the voltage signals in the substation were considered. On the other hand, for faults simulated at the rural area the signals in the recloser were considered.

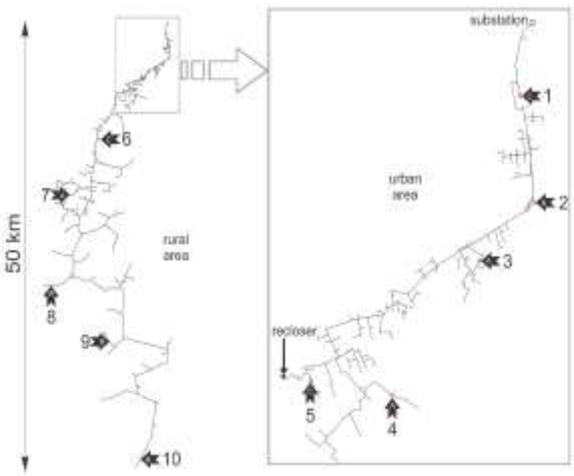

Fig. 4. Line diagram of the test distribution network.

Evaluation with Noise

The proposed aproach for HIF detection was implemented using the initialization parameters shown in the Table 1. The Fig. 5 exemplify the application of the proposed approach for the fault simulated in the point 8. After simulatins, gausian noise signals of 60 dB were added to voltage signals in order to simulate the natural noise presents in rel-life cases. In the figure can be seen that the detection signal surpasses the threshold defined by the maximum value aproximately 2 ms after the fault inception. At this moment the thresholds ramain frozen with its last value and the variable *c* (of the algorithm in Fig. 3) starts to be incremneted. As *c* attained the threshold *Tc* before the variable *t* attain the value of *Tτ*, the HIF induced transient was confiremd. This action can start the signals recording in order to realize a diagnosis and a classification of the event.

In Table 2 are sumarized the results for the HIF simulated at the tens points of the sistem shown in Fig. 4. There can be seen that in the presence of noise the algorithm detect the disturbance with less accuracy. However, the registered errors are not considered as significant for diagnosis and protection purposes.

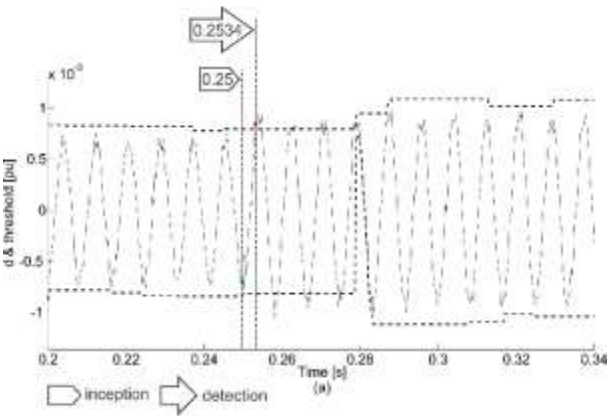

Fig. 5. Detection signal of the fault at point 8 with SNR = 60 dB

Table 1 Initialization parameters

Algorithm parameter	Value [samples]
Ns	64
Ds	32
Tc	16
Tτ	128
η	0.1*

*Value in p.u.

Table 2 Results of the detection algorithm

Faulted Point	Faulted Phase	Fault inception [ms]	Fault detection instant [ms]		
			Signal to Noise Ration [dB]		
			Inf	70	60
1	C	25	25.44	27.68	23.26
2	B	26	26.2	26.43	22.89
3	A	24	24.04	24.04	23.15
4	A	24	24.04	24.04	24.04
5	C	24	24.97	25.05	22.94
6	C	245	24.97	25.07	25.4
7	A	25	25.03	25.3	24.9
8	B	25	25.34	25.29	25.34
9	B	25	25.39	25.29	25.1
10	B	25	25.34	25.1	25.29

CONCLUSIONS

Power distribution networks fault detection is of great importance for society. Specially, HIF detection presents great challenge because of its smooth characteristics. For this reason, utilities are focusing their attention on develop techniques capable to detect these fault types in efficient manners. Noise is unavoidable in real-life applications and is the principal issue that any detection technique must tackle.

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 HIF on modeled real distribution system. Results shows that the proposed algorithm is able to detect the HIF induced transients inclusive with the presence of noise.

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