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Piotr PIERZ

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Institute of Electrical Power Engineering
Wrocław University of Technology
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
phone: +48 71 320 26 55, fax: +48 71 320 26 56
www: http://www.ie.pwr.wroc.pl/; e-mail: Inst.Energ@pwr.wroc.pl

OFICYNA WYDAWNICZA POLITECHNIKI WROCŁAWSKIEJ
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław
http://www.oficyna.pwr.wroc.pl
e-mail: oficwyd@pwr.wroc.pl
zamawianie.ksiazek@pwr.wroc.pl

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Park's transformation,
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Renato Gonçalves FERRAZ*, Leonardo Ulises IURINIC*,
André Darós FILOMENA*, Arturo Suman BRETAS*

PARK'S TRANSFORMATION BASED FORMULATION FOR POWER SYSTEMS TRANSIENTS DETECTION

This paper presents proposed developments of a new formulation and a full algorithm for transient detection by applying Park's transformation. This approach consist in transforming three-phase voltage or current signals into Park's components known as direct, quadrature, and zero axes components. The input signals are local measurements of a power transmission or distribution system. Then, transients are superimposed in three-phase signals that can be detected in Park's components through the finite difference between samples. A full algorithm for the transient detection is presented and envisions the possibility of being applied in real time. In order to demonstrate the proposed algorithm's performance, four case studies are considered: *capacitor energizing*, *distribution transformer energizing*, *permanent resistive fault*, and *high impedance fault*. These cases were simulated on a typical Brazilian sub-transmission line using Alternative Transient Program. As demonstrated by the case studies, the proposed formulation introduces further improvements for transient detection in power systems.

1. INTRODUCTION

It is well known that rapid changes in circuit states create electromagnetic transients seen in the system variables. The term transient indicates an event that is undesirable but only momentary in nature, disappearing during the transition from one steady state to another. Common sources of electromagnetic transients in power systems are lightings, faults, and switching operations. They create impulsive or oscillatory transients that can affect the performance of equipment or damage their electrical insulation [1].

Transient waveforms contain frequency components besides the fundamental frequency that characterizes the phenomenon that produced the transient. In power sys-

* Electrical Engineering Department, Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

tems, phenomena like faults are common and can cause, between others, system currents increase.

Detection of transients in power systems can initiate relay tripping or fault location methods. The correct detection is very important to determine the exact time when these phenomena began.

Many approaches are proposed in the literature to detect a transient or an abnormal system condition. The method application depends on the particular problem to be solved. The easiest to implement methods are based on sample-by-sample or cycle-by-cycle derivatives of currents or voltages signals. When this derivative overruns a pre-set value, an auxiliary counter starts to count. This counter is incremented by the absolute value of the derivative and confirms the event when it reaches another pre-set threshold [2].

Energy variations in a certain frequency band can be used as an indicator of anomalies in the system. Specific values of relative increase in harmonics can be used to detect the presence of a High Impedance Faults (HIF) or capacitor-bank switching [3]. Characteristics in the low frequency spectrum, given by 2nd and 3rd harmonics, can also be used to detect abnormal conditions produced by HIF [4]. These frequency methods can effectively detect the presence of transients by analyzing the frequency spectrum in a fixed sample window. Nonetheless, if time resolution is very poor they cannot provide with acceptable precision the beginning and end of the transient. Reference [5] shows a clear example of using Discrete Wavelet Transform (DWT) to detect transient events. The theory of wavelets filter banks is well presented and a high impedance fault can be distinguished from a capacitor-bank switching by analysis of the periodicity of the peaks. In [6] the imaginary part of the Morlet-type mother wavelet is used to create a band-pass filter with a central frequency determined by system parameters. A specific relation among ground voltage phases and currents is used to identify healthy feeders from one disturbed by a HIF. Wavelets can also be combined with singular value decomposition and Shannon entropy concepts creating a technique called Wavelet Singular Entropy (WSE) [7]. This technique basically indicates the complexity of an analyzed signal in the time-frequency domain. When a WSE increases above a particular threshold, the transient is detected and also classified by comparing the WSE of each phase. Sometimes it is preferred to detect or record only a specific type of event based on voltage measurements such as a voltage dip. Wavelet coefficients exactly points out the beginning and end of voltage dip exactly, but the high-frequency noise present are also detected. Thus, some classification criteria such as wavelet networks [8] or Kalman filter [9] must be used. In [10] an algorithm is presented for a fault location in transmission lines where the transient detection is based on the Park's transformation. However, this work does not present a theoretical approach about the transient detection through Park's transformation. An analytical study of Park's transformation contextualized on electric power system transient assessment is presented in [11]. Nevertheless, this study is performed considering the transient signal in only one phase of a set of voltages signals.

Several state-of-the-art proposed techniques are interested in power systems linear faults and normal switching detection. High impedance faults detection however is still a major challenge. A generalized approach that contributes to the further improvement of new techniques for electromagnetic transient detection in power systems is the main goal of this paper. Considering this, a Park's transformation based formulation applied to three phase voltages signals is developed and presented. Following, the equations are analyzed in detail considering some important conditions of power systems. Finally, several examples of transient signals generated by faults and switching operations in electric power system are presented. These signals were generated by Alternative Transient Program (ATP) simulations and are used to exemplify the use of the proposed formulation performance.

2. PARK'S TRANSFORMATION: TRANSIENT DETECTION

Park's transformation relates variables defined in a static reference frame with variables defined in a rotating reference frame. The most known application of the transformation is in analysis of rotating electric machines, turning the variables inductances of the stator in constant inductances on a rotating reference with synchronous speed [12]. Figure 1 illustrates this application, where q-axis and d-axis are the quadrature and direct axes respectively, ω is the angular power frequency and θ is the angle between phase a and direct axes.

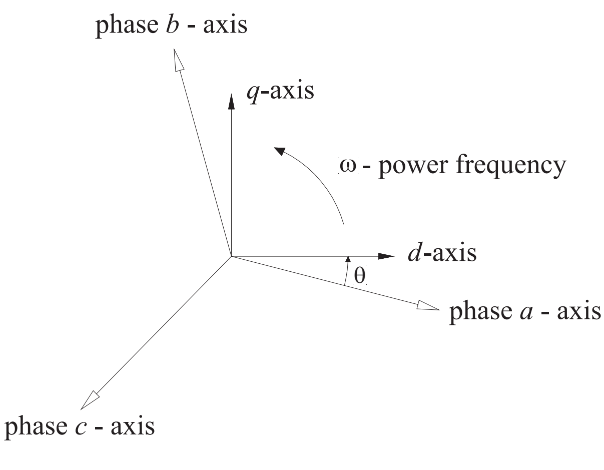

Fig. 1. Diagram of a three-phase system and dq components

Park's transformation matrix $\boldsymbol{T}_p$ can be expressed as [12]:

$$T_p = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t + \theta) & \cos(\omega t - \frac{2\pi}{3} + \theta) & \cos(\omega t + \frac{2\pi}{3} + \theta) \\ -\sin(\omega t + \theta) & -\sin(\omega t - \frac{2\pi}{3} + \theta) & -\sin(\omega t + \frac{2\pi}{3} + \theta) \\ \sqrt{1/2} & \sqrt{1/2} & \sqrt{1/2} \end{bmatrix} \tag{1}$$

where ω is the angular power frequency, t is the time instant, and θ is the angle between phase a and direct axes.

The method allows the transformation from the abc phases to the $dq0$ components in the following matrix form [12]:

$$V_{dq0} = T_p \cdot V_{abc} \tag{2}$$

where:

$\boldsymbol{V}_{dq0} = [v_d \; v_q \; v_0]^{\mathrm{T}}$ is the vector of signals $dq0$;

v_d, v_q, and v_0 are the components of direct, quadrature, and zero axes, respectively;

$\boldsymbol{V}_{abc} = [v_a \; v_b \; v_c]^{\mathrm{T}}$ is the vector of abc signals;

v_a, v_b, and v_c are the signals of the phases a, b, and c, respectively.

The detection of electromagnetic transients due to switching actions, energizing operations, faults, and lightning in a power system can be the initial process to differentiate between normal events and potentially damaging events. To demonstrate the property of the Park's transformation to detect transient signals in power systems, consider the following set of voltage signals from a three-phase system with electromagnetic transients in all phases as:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} V_{ma} \cos(\omega t) + f_a(t) \\ V_{mb} \cos(\omega t - 2\pi/3) + f_b(t) \\ V_{mc} \cos(\omega t + 2\pi/3) + f_c(t) \end{bmatrix} \tag{3}$$

where:

$f_a(t)$, $f_b(t)$, and $f_c(t)$ are the functions that represent the electromagnetic transient signal in phases a, b, and c, respectively;

V_{ma}, V_{mb}, and V_{mc} are the maximum values of signals of the phases a, b, and c, respectively.

Transients were considered in all phases because they are usually coupled. Therefore, an event in one phase is propagated to the others.

Park's transformation according to (2) is applied to (3) and after the application of some trigonometric identities [13], results in v_0, v_d, and v_q components as:

$$v_0 = \sqrt{\frac{2}{3}} \cdot \sqrt{\frac{1}{2}} \left\{ \left[V_{ma} \cos(\omega t) + V_{mb} \cos\left(\omega t - \frac{2\pi}{3} \right) + V_{mc} \cos\left(\omega t + \frac{2\pi}{3} \right) \right] + \left[f_a(t) + f_b(t) + f_c(t) \right] \right\} \tag{4}$$

$$v_d = \sqrt{\frac{2}{3}} \cdot \left\{ \begin{array}{l} \frac{1}{2}\left(V_{ma} + V_{mb} + V_{mc}\right)\cos(\theta) + \\ \left[\frac{1}{2}\left(V_{ma} - \frac{1}{2}V_{mb} - \frac{1}{2}V_{mc} \right)\cos(2\omega t + \theta) + \frac{\sqrt{3}}{2}\left(V_{mc} - V_{mb}\right)\sin(2\omega t + \theta) \right] + \\ \left[\left(f_a(t) - \frac{1}{2} f_b(t) - \frac{1}{2} f_c(t) \right)\cos(2\omega t + \theta) - \frac{\sqrt{3}}{2}\left(f_b(t) + f_c(t)\right)\sin(\omega t + \theta) \right] \end{array} \right\} \tag{5}$$

$$v_q = \sqrt{\frac{2}{3}} \cdot \left\{ \begin{array}{l} \frac{1}{2}\left(V_{ma} + V_{mb} + V_{mc}\right)\sin(\theta) + \\ \left[\frac{1}{2}\left(V_{ma} - \frac{1}{2}V_{mb} - \frac{1}{2}V_{mc} \right)\sin(2\omega t + \theta) + \frac{\sqrt{3}}{2}\left(V_{mb} - V_{mc}\right)\cos(2\omega t + \theta) \right] + \\ \left[\left(f_a(t) - \frac{1}{2} f_b(t) - \frac{1}{2} f_c(t) \right)\sin(\omega t + \theta) + \frac{\sqrt{3}}{2}\left(f_c(t) + f_b(t)\right)\cos(\omega t + \theta) \right] \end{array} \right\} \tag{6}$$

Again applying trigonometric relationships [13] on (4), (5) and (6), the following expressions are obtained:

$$v_0 = k_1 \cos(\omega t - \delta_0) + \frac{\sqrt{3}}{2}\left[f_a(t) + f_b(t) + f_c(t) \right] \tag{7}$$

where:

$$k_1 = \sqrt{k_2^2 + k_3^2} \tag{8}$$

$$k_2 = \frac{\sqrt{3}}{3}\left(V_{ma} - \frac{1}{2}V_{mb} - \frac{1}{2}V_{mc} \right) \tag{9}$$

$$k_3 = \frac{1}{2}\left(V_{mb} - V_{mc}\right) \tag{10}$$

and

$$\delta_0 = \tan^{-1}\left(k_3 / k_2\right) \tag{11}$$

Similarly, (5) may be rewritten as:

$$v_d = \sqrt{\frac{2}{3}}\left[V\cos(\theta) + k_4\cos(2\omega t + \theta - \delta) + m(t)\cos(\omega t + \theta - \delta_T(t))\right] \tag{12}$$

where:

$$V = \frac{1}{2}\left(V_{ma} + V_{mb} + V_{mc}\right) \tag{13}$$

$$k_4 = \sqrt{k_5^2 + k_6^2} \tag{14}$$

$$k_5 = \frac{1}{2}\left(V_{ma} - \frac{1}{2}V_{mb} - \frac{1}{2}V_{mc}\right) \tag{15}$$

$$k_6 = \frac{1}{2}\frac{\sqrt{3}}{2}\left(V_{mc} - V_{mb}\right) \tag{16}$$

$$\delta = \tan^{-1}\left(k_6 / k_5\right) \tag{17}$$

$$m(t) = \sqrt{m_1^2(t) + m_2^2(t)} \tag{18}$$

$$m_1(t) = f_a(t) - \frac{1}{2}f_b(t) - \frac{1}{2}f_c(t) \tag{19}$$

$$m_2(t) = \frac{\sqrt{3}}{2}\left[f_b(t) - f_c(t)\right] \tag{20}$$

and

$$\delta_T(t) = \tan^{-1}\left(m_2(t) / m_1(t)\right) \tag{21}$$

Likewise, (6) may be rewritten as:

$$v_q = \sqrt{\frac{2}{3}}\left[V\sin(\theta) + k_4\sin(2\omega t + \theta - \delta) + m(t)\sin(\omega t + \theta - \delta_T(t))\right] \tag{22}$$

Thus, the application of Park's transformation on (3) results in:

$$\begin{bmatrix} v_0 \\ v_d \\ v_q \end{bmatrix} = \begin{bmatrix} k_1 \cos(\omega t - \delta_0) + \dfrac{\sqrt{3}}{3}\left[f_a(t) + f_b(t) + f_c(t)\right] \\ \sqrt{\dfrac{2}{3}}\left[V\cos(\theta) + k_4 \cos(2\omega t + \theta - \delta) + m(t)\cos(\omega t + \theta - \delta_T(t))\right] \\ -\sqrt{\dfrac{2}{3}}\left[V\sin(\theta) + k_4 \sin(2\omega t + \theta - \delta) + m(t)\sin(\omega t + \theta - \delta_T(t))\right] \end{bmatrix} \tag{23}$$

The relationship between v_d and v_q as orthogonal projections of the same vector can be explicitly seen in (23). Function $m(t)$ can be understood as composition point by point of functions $m_1(t)$ and m_2(t) whose angle is $\delta_T(t)$. They only depend on the existence of transient signals superimposed with fundamentals ones. On the other hand, because parameters k_2 and k_3 depend only on the amplitude of fundamental components, it is possible to interpret them as components of a vector with angle δ_0 and modulus k_1. The same can be said of the parameters k_5 and k_6 in relation to k_4 and angle δ. Angle θ, as shown in Fig. 1, is the angle between phase a and direct axes. It is a constant with a stochastic value depending on the moment when Park's transformation is applied. However, to simplify the presented analysis of v_0, v_d and v_q components, this angle will be considered zero.

3. EQUATIONS ANALYSIS

This section will analyze the set of equations (23) from the perspective of important power systems operating conditions.

A. Balanced System Operating without Electromagnetic Transient

A balanced system operating in the absence of an electromagnetic transient is given as $V_{ma} = V_{mb} = V_{mc} = V_m$ and $f_a(t) = f_b(t) = f_c(t) = 0$. For these conditions and analyzing (23) it is possible to verify that:

$$v_0 = 0 \tag{24}$$

$$v_d = \sqrt{\frac{2}{3}} V\cos(\theta) = \frac{\sqrt{6}}{2} V_m \cos(\theta) \tag{25}$$

and

$$v_q = -\sqrt{\frac{2}{3}} V\sin(\theta) = -\frac{\sqrt{6}}{2} V_m \sin(\theta) \tag{26}$$

In other words, the application of Park's transformation to a set of signals at the fundamental frequency of a balanced system results only in a DC level of v_d, and v_q components that depends on angle θ.

B. Balanced System Operating with Electromagnetic Transient

A balanced system operating during the presence of an electromagnetic transient is given as $V_{ma} = V_{mb} = V_{mc} = V_m$ and $f_a(t)$, $f_b(t)$ and $f_c(t)$ with nonzero values. For these conditions and by analyzing (23) is possible to verify that:

$$v_0 = \frac{\sqrt{3}}{3}\left[f_a(t) + f_b(t) + f_c(t)\right] \tag{27}$$

$$v_d = \sqrt{\frac{2}{3}}\left[V\cos(\theta) + m(t)\cos(\omega t + \theta - \delta_T(t))\right] = \sqrt{\frac{2}{3}}\left[\frac{3}{2}V_m\cos(\theta) + m(t)\cos(\omega t + \theta - \delta_T(t))\right] \tag{28}$$

and

$$v_q = -\sqrt{\frac{2}{3}}\left[V\sin(\theta) + m(t)\sin(\omega t + \theta - \delta_T(t))\right] = -\sqrt{\frac{2}{3}}\left[\frac{3}{2}V_m\sin(\theta) + m(t)\sin(\omega t + \theta - \delta_T(t))\right] \tag{29}$$

That is, the application of Park's transformation to a set of signals at the fundamental frequency of a balanced system operating during the presence of electromagnetic transient results in:

- the sum of the transient signals for the v_0 component, multiplied by a constant;
- a constant plus a combination of transient signal term for the v_d and v_q.

C. Unbalanced System Operating without Electromagnetic Transient

An unbalanced system operating in the absence of an electromagnetic transient is given as $V_{ma} \neq V_{mb} \neq V_{mc}$ and $f_a(t) = f_b(t) = f_c(t) = 0$. For these conditions and by analyzing (23) it is possible to verify that:

$$v_0 = k_1\cos(\omega t - \delta_0) \tag{30}$$

$$v_d = \sqrt{\frac{2}{3}}\left[V\cos(\theta) + k_4\cos(2\omega t + \theta - \delta)\right] \tag{31}$$

and

$$v_q = -\sqrt{\frac{2}{3}}\left[V\sin(\theta) + k_4\sin(2\omega t + \theta - \delta)\right] \tag{32}$$

The application of Park's transformation for the conditions described above results in:

- a cosine with fundamental frequency in v_0 component;
- a DC level plus a second harmonic in v_d and v_q component;

D. Unbalanced System Operating with Electromagnetic Transient

An unbalanced system operating during the presence of electromagnetic transient is given as $V_{ma} \neq V_{mb} \neq V_{mc}$ and $f_a(t)$, $f_b(t)$ and $f_c(t)$ with nonzero values. For these conditions and by analyzing (23) is possible to verify that:

$$v_0 = k_1 \cos(\omega t - \delta_0) + \frac{\sqrt{3}}{3}\left[f_a(t) + f_b(t) + f_c(t)\right] \tag{33}$$

$$v_d = \sqrt{\frac{2}{3}}\left[V\cos(\theta) + k_4 \cos(2\omega t + \theta - \delta) + m(t)\cos(\omega t + \theta - \delta_T(t))\right] \tag{34}$$

and

$$v_q = -\sqrt{\frac{2}{3}}\left[V\sin(\theta) + k_4 \sin(2\omega t + \theta - \delta) + m(t)\sin(\omega t + \theta - \delta_T(t))\right] \tag{35}$$

In other words, the application of Park's transformation for the conditions described above results in:

- the v_0 component is a fundamental frequency and transient signals combination;
- the v_d and v_q components have the following combination:
  - DC level;
  - second harmonic of the fundamental frequency;
  - modified frequency and amplitude combination of transient signals.

At this point can be clearly verified that conditions described in items *A*, *B*, and *C* are particular cases of the condition described in *D*. For a better understanding of the Park's application, consider the following example.

F. Example

Consider a set of balanced voltages, all with an amplitude of 1 pu, with a momentary oscillatory transient in phase *a*. Such a transient signal is a signal whose energy is concentrated in certain ranges of time and frequency ranges. Such a signal may be mathematically represented by a Gaussian envelope, which is characterized in this example by a standard deviation of 2 ms, centered at 2.6 ms and modulated by a cosine function of 500 Hz according to:

$$f_a(t) = 0.5 \cdot e^{-\frac{1}{2}\left(\frac{t-0.026}{0.002}\right)} \cos(2\pi \cdot 500 \cdot t) \tag{36}$$

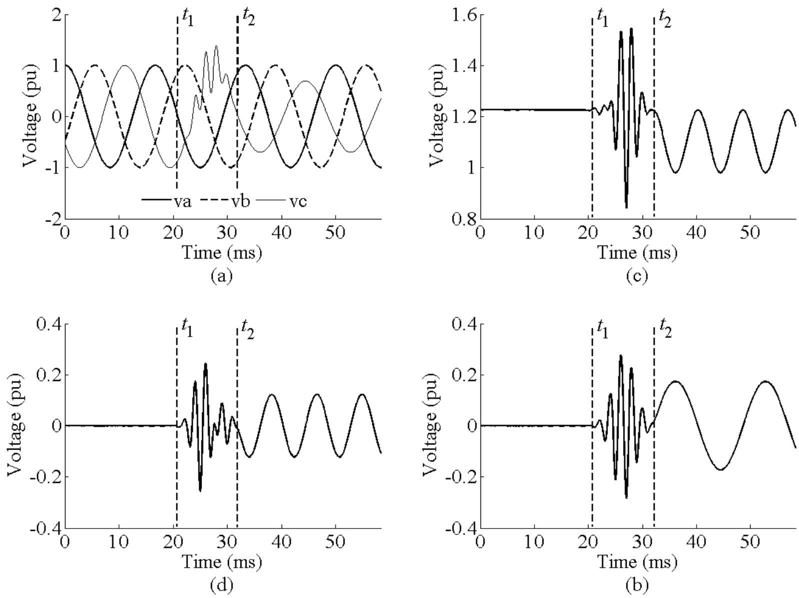

Fig. 2. Park's transformation: (a) phase voltages; (b) v_0; (c) v_d; (d) v_q

Immediately before the occurrence of the transient at phase *c*, an unbalance was characterized by a voltage of phase *c* of 0.8 pu. As shown in Fig. 2, upon the beginning of the transient approximately in t_1, v_0 signal is zero and v_d and v_q signals are constant values given by (25) and (26) respectively. Before t_1, v_0 is proportional to the proper transient as shown in (27). The signals v_d and v_q are modified according to (28) and (29), not only by an amplitude modification but also by a frequency distortion. This distortion is given by multiplications of the transient component $m(t)$ with a sine and cosine. After the transient dies out at t_2, an unbalance can be seen by the aspersion of a fundamental frequency term in v_0 and second harmonics in v_d and v_q.

4. TRANSIENTS DETECTION ALGORITHM AND CASE STUDIES

Using Park's transformation to detect transients allows supervision of the power systems three phases with only one signal and eliminates the fundamental frequency effect, improving the transient detection. It is possible to use any Park's component (v_0, v_d or v_q) for detection approach, in this paper the v_d component is used.

The finite difference approximation of the derivate can be used in the v_d component for transient detection as follows:

$$c_{diff}(k) = v_d(k) - v_d(k-1) \tag{37}$$

where k is the sample number. The finite difference quantities concept is broadly used in the literature [14].

According to (31), if an unbalanced voltage condition is present an oscillation of twice the fundamental frequency in v_d is produced. This oscillation is also seen in c_{diff} and its amplitude is used as a threshold. To perform the transient detection, the square of c_{diff} is used as a way to attenuate noises and magnify transient components. In [10], c_{diff}^2 was used to attenuate noises and magnify transient components and the adaptive method was also proposed.

In order to have more control in the sensibility of the detection algorithm for the most important electromagnetic transients in power systems, a full algorithm and two threshold transient detections are presented. The basic idea is to count the times that c_{diff}^2 exceeds the adaptive threshold at some time interval. As was analyzed before in case *B* of section 3, in a case of unbalance, v_d will be composed of a second harmonic and a DC level as shown (31). As a result c_{diff} is composed only by a second harmonic. Then, the module of this second harmonic is used as the adaptive threshold. Figure 3 shows the steps of the proposed detection algorithm.

Figures 4 and 5 exemplify the algorithm showing the v_d signal, c_{diff}^2 and the adaptive threshold. The first sample of c_{diff}^2 due to a transient beginning is much larger than the threshold can be seen in Fig. 4. The second sample is below the threshold, but the four subsequent samples are above the threshold. For the five samples above the threshold before time count reached the value of time threshold, the transient is confirmed and detected. In Fig. 5 a short transient occurs and is seen in v_d's signal, the first sample of c_{diff}^2 after the transient beginning is much larger than the threshold. On the other hand, because less than five samples are above the threshold before the time_count reaches the thime_threshold, the transient is not detected.

Aiming to demonstrate the proposed formulation performance, four case studies were considered: *capacitor energization*, *distribution transformer energization*, *permanent resistive fault*, and *high impedance fault*. These cases were simulated on a typical Brazilian sub-transmission line using ATP. The line is 30 km long and has a nominal voltage of 69 kV, it is connecting two substations in the state of Rio Grande do Sul. In order to simulate a situation closer to reality, also the phenomenon of travelling wave was also considered using a frequency dependent line model. Note that all stated cases are hypotheticals, only the line model is a reproduction of a real situation. For all cases is used a time_threshold of 10 and count_threshold of 5. Figure 6 shows the power system used in the case studies where the Digital Transient Recorder (DTR) is in the local terminal. The switches S_1, S_2, S_3, and S_4 are closed individually for each case.

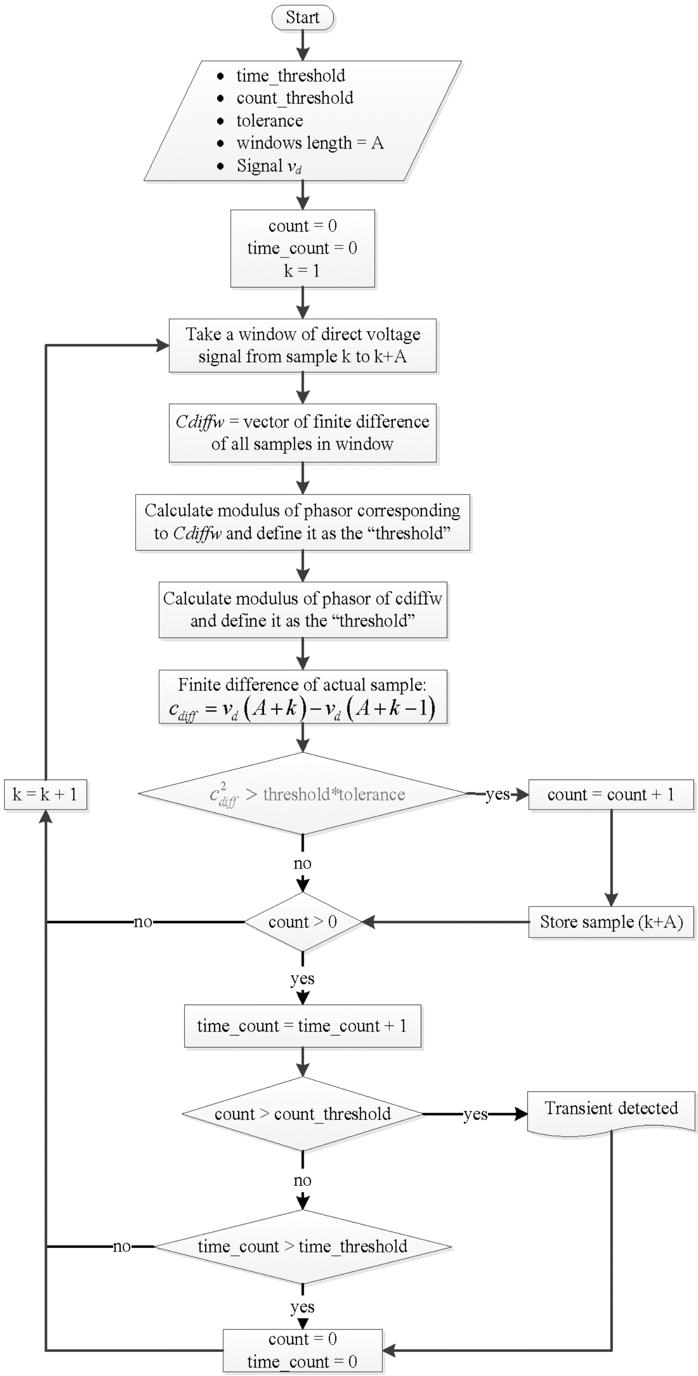

Fig. 3. Full algorithm for the transient detection

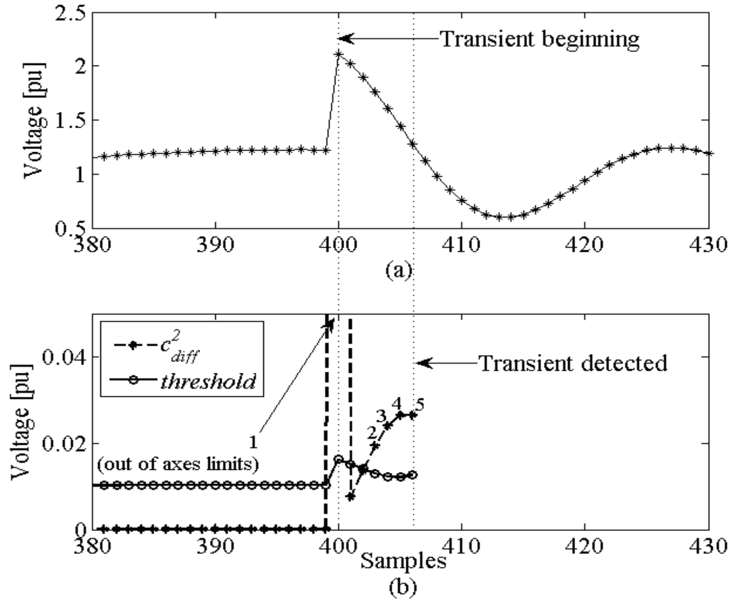

Fig. 4. Transient detection: (a) v_d component; (b) adaptive threshold

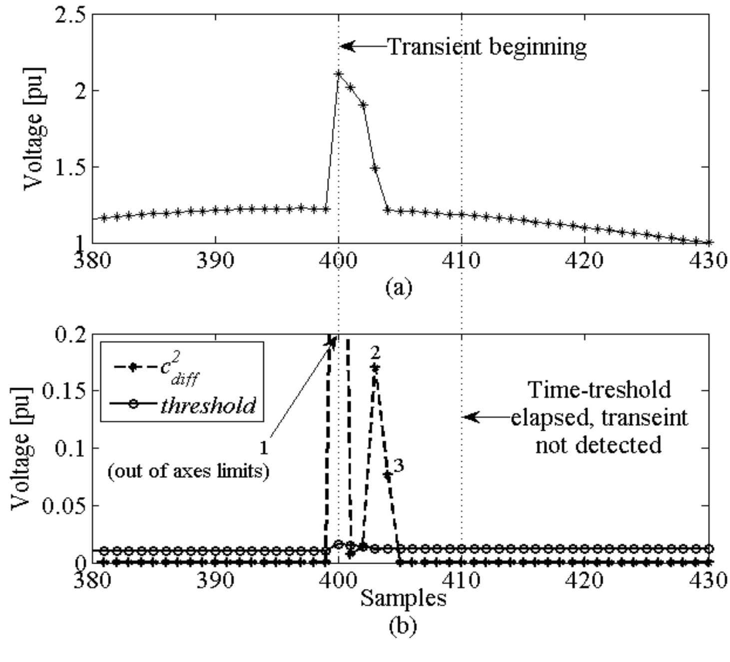

Fig. 5. Not transient detection: (a) v_d component; (b) adaptive threshold

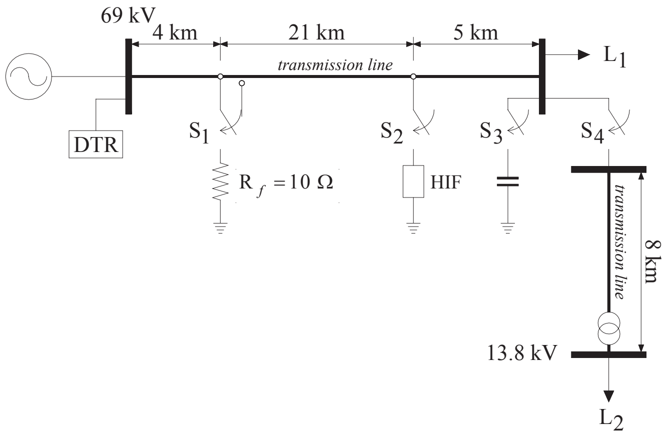

Fig. 6. Power system for case studies

A. Capacitor energization

In this case the capacitor bank was connected in parallel with a wye connection. The capacitors have 4 mS with a factor for the series resistance of 0.15. Figure 7a shows the part of v_d's signal that contain the ignition of a transient due to the capacitor bank switch. The c^2_{diff} signal and the adaptive threshold are depicted in Fig. 7b. It can be seen that the c^2_{diff} is progressively larger than the adaptive threshold up to the third sample after the transient beginning. The fourth sample is below the threshold, but

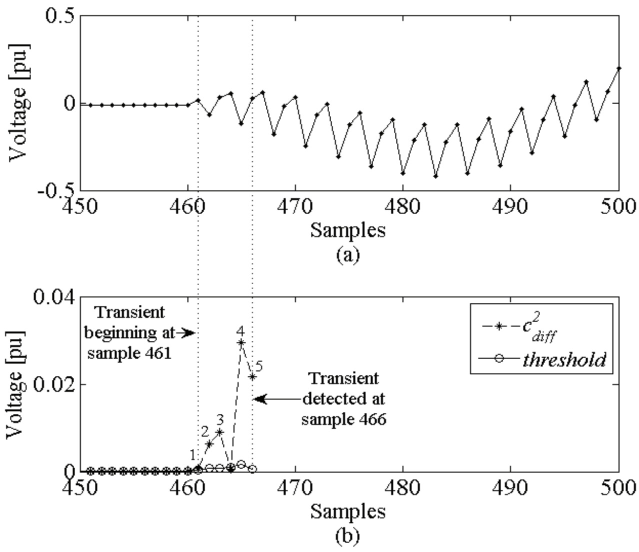

Fig. 7. Capacitor bank energizing detection: (a) v_d component; (b) adaptive threshold

fifth and sixth are above and confirm the transient detection. In this case the load had not produced an unbalance condition.

B. Transformer energization

In this case a 8 km long line was connected with a distribution transformer at the end of line with a balanced load. In Fig. 8 (b) is shown the value of count and it can be seen that the first value c_{diff}^2 after the transient beginning is much larger than the threshold. The second sample is below the threshold, but third is higher again. Subsequently oscillation due to the transient diminish and c_{diff}^2 become smaller, but always above the threshold, leading to transient confirmation at sample 466 of the v_d signal.

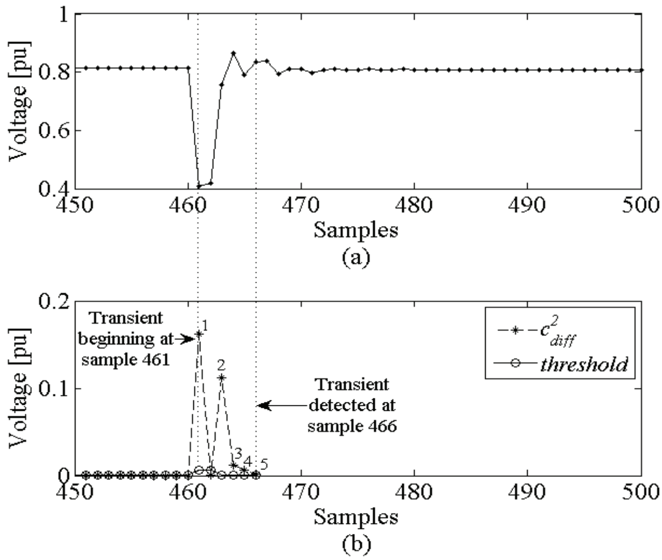

Fig. 8. Transformer energizing detection: (a) v_d component; (b) adaptive threshold

C. Permanent resistive fault

In Figure 9, the three-phase voltages from a permanent resistive fault in phase *b* at 4 km from the feeder can be seen. This confirms what was said in section one of the paper: a disturbance in one phase can produce disturbances in the others phases. As can be seen in Fig. 10 (b) oscillations due to travelling wave phenomenon are high at the beginning of the transient and first three samples of c_{diff}^2 are considerably above the threshold. The following samples are lower, but enough to confirm transient detection at sample 466 of v_d signal.

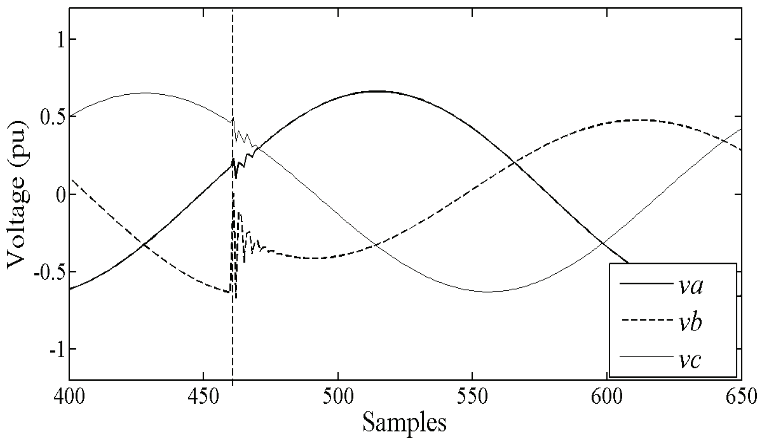

Fig. 9. Three phase voltage of single phase fault

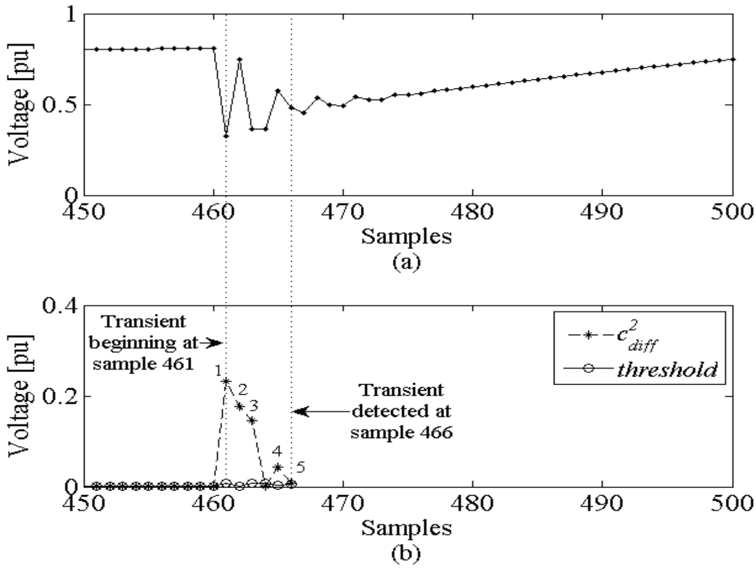

Fig. 10. Permanent resistive fault detection: (a) v_d component; (b) adaptive threshold

D. High impedance fault

A HIF modeled according to [4] was connected at 25 km from feeder in phase *b*. In this case transient was detected too with the proposed thresholds configuration. As can be seen in Fig. 12 (b), five samples after HIF inception are above the adaptive threshold, detecting the transient. As can be seen in Fig. 11 the voltage unbalance among phases is not significant, however can be seen an oscillation in v_d signal if it is calculated for more samples. As a HIF has some harmonic content, that oscillation can be explained by means of (23), replacing functions that represent transients by any harmonic component. This lead a function $m(t)$ with the same harmonic content but modified by the multiplication by a cosine with time varying phase.

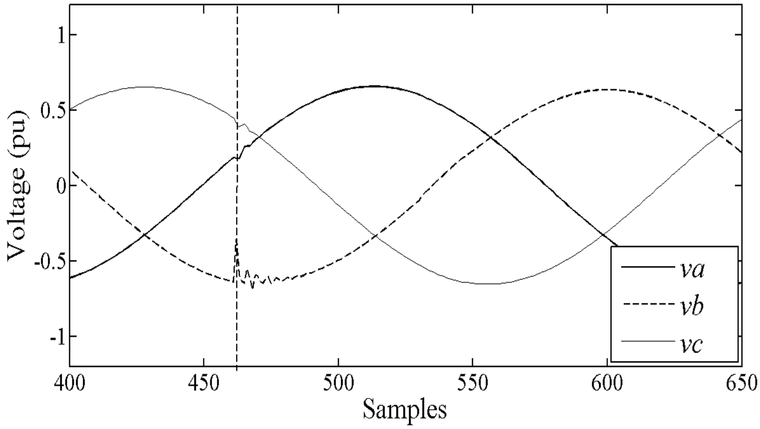

Fig. 11. Three phase voltage of single phase HIF

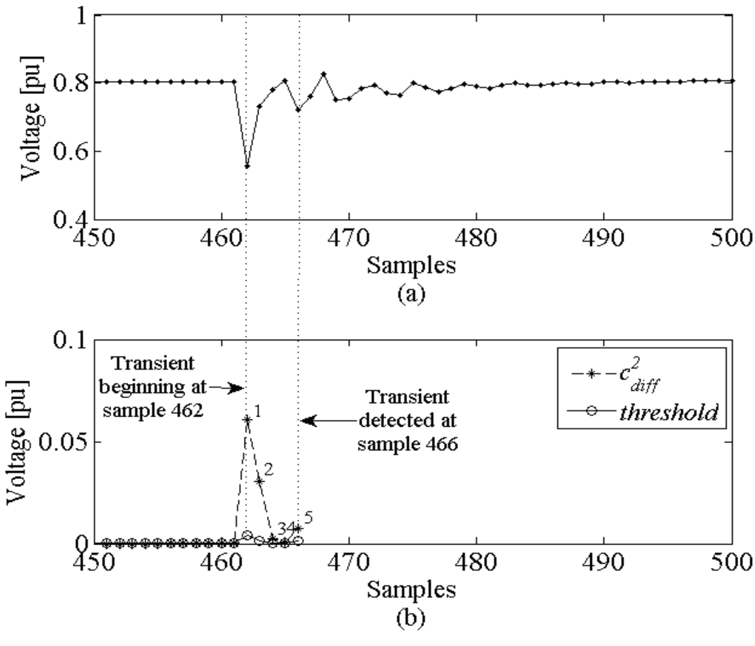

Fig. 12. HIF detection: (a) v_d component; (b) adaptive threshold

5. DISCUSSIONS

Application: In this paper, an analytical approach and a full algorithm for transient detection using the Park's transformation is presented. From the case studies shown, it is thus clear that Park's transformation is a useful and valid approach for transient detection in electrical power systems.

Advantages: Application of Park's transformation in three phase voltage signals brings some noticeable advantages. Firstly, all three phases can be monitored simultaneously by the analysis of only one signal. Secondly, when the system is operating normally (case *A* in section three), all Park's signals are constants, perturbed only in the presence of a transient (case *B* in section three). Naturally in practice it is not possible to have a perfectly equilibrated system free of noise, for this reason an adaptive threshold was presented. The algorithm has the possibility to control the sensibility of detection by means of an over-threshold samples-counter and a time-counter. Furthermore, this approach is insensitive to fault type, fault location, fault resistance, fault inception angle, switching operations or deviations in fundamental frequency of power system. Nonetheless, due to space, not all events have been presented in this work.

Limitations: The major limitation in the application of this approach is related to the frequency response of the voltage and current transformers. In fact, the transducers can introduce errors and attenuate the voltage and current signals.

Future Research: Classification and characterization of electromagnetic phenomena efficiently are classical problems in power quality engineering. Hence, future works can explore the application of Park's transformation in power quality applications. Also, the explicitly behavior of Park's components can be shown in cases of phase imbalance and the presence of harmonics. Furthermore, can also be explored the orthogonal behavior between v_d and v_q components for other applications.

6. CONCLUSIONS

A full analytical study on the Park's transformation has been presented within the context of transient detection analysis in electric power systems. In this paper it was presented a discussion of the application of Park's transformation for transient detection. The approach may use measurements of voltages or currents signals obtained in the local terminal from a power transmission or distribution systems.

The major contributions of this work are related to the presentation of the equations v_0, v_d, and v_q components that show in detail the behavior of the three-phase signals in the presence of electromagnetic transients in all phases. The analysis of these equations was essential in order to understand the nature and response of its solutions for some important operation conditions of the power system. Another important contribution is the presentation of a full algorithm for transient detection.

It is important to point out that this approach is insensitive to the event type and can be used for the detection of transient signals of the some typical operational situations in power systems. As demonstrated by the case studies, it is clear that Park's transformation introduces a further improvement for transient detection in power systems.

REFERENCES

[1] Institute of Electrical and Electronics Engineers, *Recommended practice for monitoring electric power quality: Std. 1159*, IEEE Power Engineering Society, New York 1995.

[2] SAHA M.M., IŻYKOWSKI J., ROSOŁOWSKI E., *Fault Location on Power Network*, Springer--Verlag, New York 2010.

[3] KIM C.J., RUSSEL B.D., *Harmonic Behaviour During Arcing Faults on Power Distribution Feeders*, Electric Power Systems Research, Vol. 14, 1988, 219–225.

[4] EMANUEL A.E., GULACHENSKI E.M., *High Impedance Fault Arcing on Sandy Soil in 15 kV Distribution Feeders: Contribution to the evaluation of the low frequency spectrum*, IEEE Transactions on Power Delivery, Vol. 5, No. 2, 1990, 676–686.

[5] WAI D.C.T., YIBIN X., *A Novel Technique for High Impedance Fault Identification*, IEEE Transactions on Power Delivery, Vol. 13, No. 3, 1998, 738–744.

[6] MICHALIK M., REBIZANT W., ŁUKOWICZ M., LEE S., KANG S., *High-impedance fault detection in distribution networks with use of wavelet-based algorithm*, IEEE Transactions on Power Delivery, Vol. 21, No. 4, 2006, 1793–1802.

[7] HE Z. FU L. LIN S. BO Z, *Fault Detection and Classification in EHV Transmission Line Based on Wavelet Singular Entropy*, IEEE Transactions on Power Delivery, Vol. 2, No. 4, 2010, 2156–2163.

[8] MASOUM M.A.S., JAMALI S., GHAFFARZADEH N., *Detection and Classification of Power Quality Disturbances Using Discrete Wavelet Transform and Wavelet Networks*, IET Science, Measurement and Technology, Vol. 4, 2010, 193–205.

[9] BAROS J., PÉREZ E., *Automatic Detection and Analysis of Voltage Events in Power Systems*, IEEE Transactions on Instrumentation and Measurement, Vol. 55, No. 5, 2006, 1487–1493.

[10] LOPES F.V., SANTOS W.C., FERNANDES D., Jr., *An adaptive fault location method for smart distribution and transmissions grids*, IEEE PES Conference on Innovative Smart Grid Technologies (ISGT Latin America), Medellin, 19–21 Oct. 2011.

[11] FERRAZ R.G., IURINIC L.U., FILOMENA A.D., BRETAS A.S., *Park's transformation analytical approach of transient signal analysis for power systems*, North American Power Symposium (NAPS), Urbana, 9–11 Sept. 2012.

[12] KUNDUR P., *Power system stability and control*, McGraw-Hill, New York 1994, 83, eq. 3.118.

[13] SPIEGEL M.R., *Mathematical handbook of formulas and tables*, McGraw-Hill, New York 1968, p. 15, eq. 5.35, p. 17, eqs. 5.66, 5.67.

[14] BENMOUYAL G., MAHSEREDJIAN J., *A combined directional and faulted phase selector element based on incremental quantities*, IEEE Transactions on Power Delivery, Vol. 16, Iss. 4, 2001, 478–484.