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Fault detection in a three-phase system grid connected using SOGI structure to calculate vector components

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Abstract. Fault detection algorithms are very important in grid connected systems. They are used to analyze a three-phase system behavior in real time. When something wrong happens, they start some procedures to avoid the collapse. A three-phase system cannot be considered a simply sum of three independent phases, which leads us to apply some vector transform to obtain a more elegant representation of systems. A control system grid connected is based on the vector transform. In this paper we analyze a fault detection performance between some vector transform algorithms, and present a good way to accomplish these transforms using a SOGI (Second Order Generalized Integrator).

Key words

SOGI, grid connected, vector transform.

Introduction

Due to increasing global demand for energy, the depletion of natural resources of the planet (oil, coal, ...), in addition to concern over global warming, researchers worldwide are dedicated to provide clean and renewable energy (Xavier, 2013). In this context, electrical energy that can be considered one of the most important ways to distribute energy, have two main problems: Efficient generation and grid connection. A photovoltaic panel and wild turbines are today the most widely used way to generate renewable electrical energy. Thus, it's necessary a big concern to interconnect these systems in the electrical grid. A distributed generation system, when connected with a electrical grid, need to have a synchronism and protection system, to prevent a big problems in the grid. Given the great complexity of the electrical grid systems, and a big amount of the interconnected generates system, have consider that existing controls are capable to predict unbalance phase, harmonics and even frequency changing in the power system. Thus, it requires algorithms and math tools to keep the grid under control, or simply detect disturbs in the source grid. Between the existing algorithms, the most suitable are processed using a mathematical transforms below:

- Symmetrical components transform in time domain (Lyon, 1937);
- αβ transform (Clarke, 1950);
- dq transform (Park, 1927);
- Symmetric Positive and Negative Components in αβ transform (Irani, 2003).

1. Three-Phase Transform

A. Symmetrical components transform in time domain

The method of decomposition into symmetric in the time domain (Lyon, 1937) components is an extension of the decomposition method in the frequency domain (Fortescue, 1918). Knowing that V_{abc} é the sum of their symmetrical components, have:

$$\begin{bmatrix} v_a^+ \\ v_b^+ \\ v_c^+ \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ \alpha^2 & 1 & \alpha \\ \alpha & \alpha^2 & 1 \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_a^- \\ v_b^- \\ v_c^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha^2 & \alpha \\ \alpha & 1 & \alpha^2 \\ \alpha^2 & \alpha & 1 \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} v_a^0 \\ v_b^0 \\ v_c^0 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3}$$

1) *Balanced Systems*

As shown in **Fig. 1**, in a system balanced, only the positive symmetric component (v_{abc}^+) is equal system voltages (v_{abc}), and the Negative and Zero components has null value.

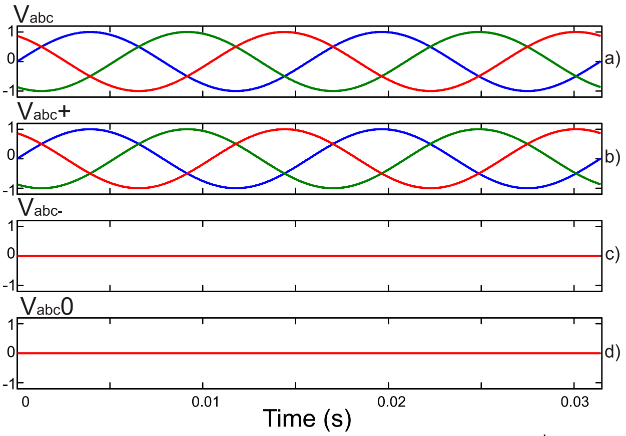

Fig. 1: Balanced three-phase system. a) v_{abc}; b) v_{abc}^{+}; c) v_{abc}^{-}; d) v_{abc}^{0}.

2) *Unbalanced System*

Looking at **Fig. 2**, we saw that in an unbalanced three-phase system system (V_{abc}) is decomposed symmetrical components positive (V_{abc}^{+}), negative (V_{abc}^{-}) and zero (V_{abc}^{+0}) and have values peak proportional to the imbalance found.

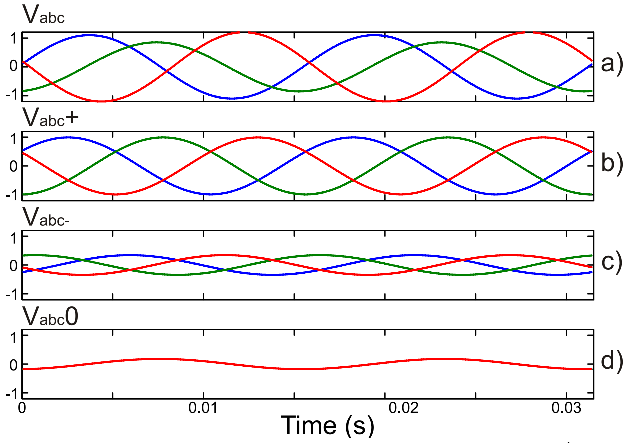

Fig. 2: Unbalanced Three-Phase System. a) $\boldsymbol{V_{abc}}$; b) $\boldsymbol{V_{abc}^{+}}$; c) $\boldsymbol{V_{abc}^{-}}$; d) $\boldsymbol{V_{abc}^{+0}}$.

B. *αβ Components*

This mathematical transformation (Clarke, 1950) is widely used in electrical engineering to simplify the analysis of three-phase systems. It transforms a three-phase system into an equivalent two-phase system, with orthogonal imaginary axis and the real axis. This processing is applied in the time domain by multiplying the transformation matrix $[T_{\alpha\beta 0}]$ by the vector of voltages $[v_a, v_b, v_c]^T$.

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (4)$$

Note that after applying the transform in a three-phase system voltages abc we can write $v_\alpha^2 + v_\beta^2 + v_0^2 = v_a^2 + v_b^2 + v_c^2$
and with respect to the resulting power we have:

$$p = v_{\alpha\beta 0} . i_{\alpha\beta 0} = v_{abc} . v_{abc} \quad (5)$$

1) *Balanced systems*

Fig. **3** shows the decomposition into α β of a balanced system abc, the magnitude of Vα and Vβ calculated as $\sqrt{V_\alpha^2 + V_\beta^2}$ stays constant, and the angle ϴ is calculated as $\tan^{-1}\left(\frac{V_\alpha}{V_\beta}\right)$, which is a form of saw tooth wave of perfect.

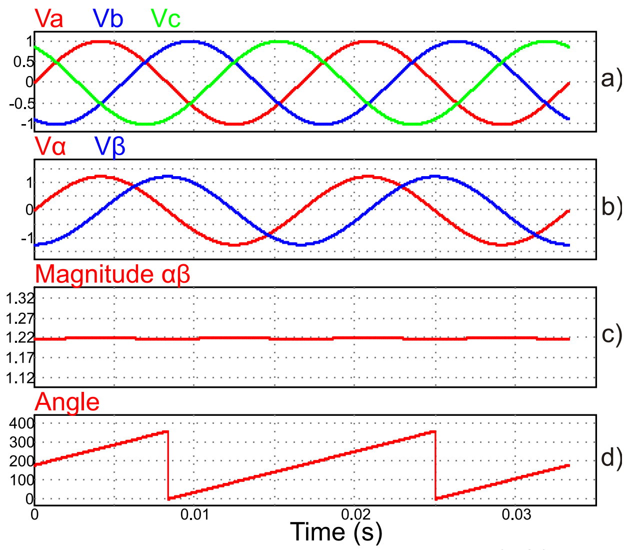

Fig. 3: Balanced System: a) $\boldsymbol{V_{abc}}$; b) $\boldsymbol{V_{\alpha\beta}}$; c) | αβ |; d) αβ angle.

2) *Unbalanced systems*

Fig. **4** shows a decomposition into α β of a balanced system abc, the magnitude of Vα and Vβ calculated as $\sqrt{V_\alpha^2 + V_\beta^2}$ is not constant and the angle calculated as $\tan^{-1}\left(\frac{V_\alpha}{V_\beta}\right)$ is not a perfect saw tooth wave.

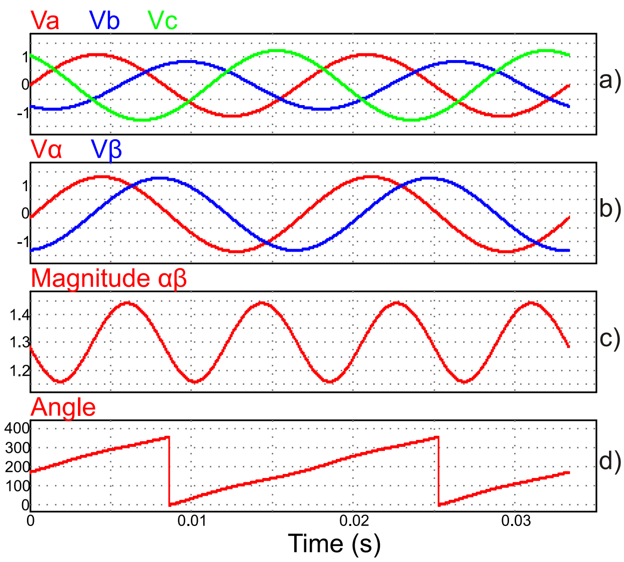

Fig. 4: Unbalanced System: a) $\boldsymbol{V_{abc}}$; b) $\boldsymbol{V_{\alpha\beta}}$; c) |αβ|; d) αβ angle.

C. *dq Components*

Another widely used for the math processing analysis phase systems is transformed dq (Park, 1927), where the vector components can be converted into synchronous dq vector components using the transformation matrix $[T_{dq0}]$ given by:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (6)$$

and powers as

$$v_d^2 + v_q^2 + v_0^2 = v_\alpha^2 + v_\beta^2 + v_0^2 = v_a^2 + v_b^2 + v_c^2 \qquad (7)$$

1) Balanced Systems

As shown in Fig. **5**, in a balanced three-phase systems, the d component is zero and the q component remains constant in the peak value of the voltage abc.

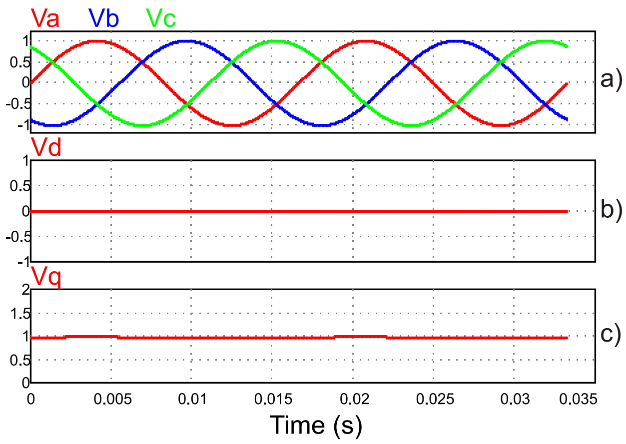

Fig. 5: Balanced System a) $\boldsymbol{V_{abc}}$; b) $\boldsymbol{V_d}$; c) $\boldsymbol{V_q}$.

2) Unbalanced Systems

Fig. **6** in unbalanced three-phase systems, the d component oscillates around zero, and a component q oscillates around the peak value of voltages abc.

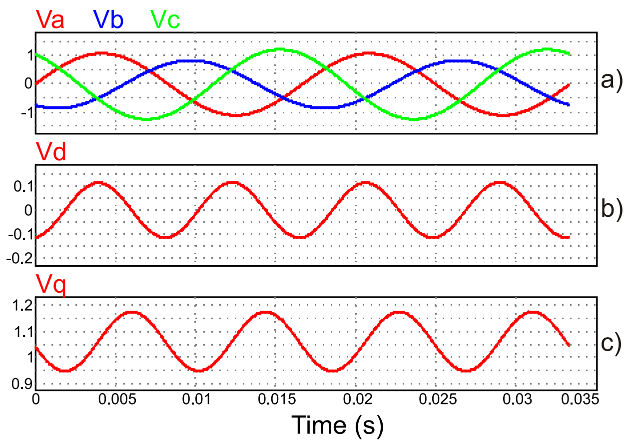

Fig. 6: Unbalanced System: a) $\boldsymbol{V_{abc}}$; b) $\boldsymbol{V_d}$; c) $\boldsymbol{V_q}$.

D. Symmetric Positive and Negative Components in αβ transform.

In order to minimize the computational effort in detecting faults in three-phase systems, rather than calculate the positive and negative-phase components of the phases a, b and c individually to further analyze each phase, we calculate the $\alpha\beta$ symmetrical components, than we can analyze the system detecting faults in amplitude, frequency and phase shift between phases. We can find $V_{\alpha\beta}^{+}$ and $V_{\alpha\beta}^{-}$ using equation (**4**) to calculate v_α and v_β than using (**8**) and (**9**) to get $v_{\alpha\beta}^{+}$ and $v_{\alpha\beta}^{-}$ and after all, use (**10**) and (**11**).

$$v_{\alpha\beta}^{+} = \frac{1}{2}\begin{bmatrix} 1 & -q \\ q & 1 \end{bmatrix} v_{\alpha\beta} \qquad (8)$$

$$v_{\alpha\beta}^{-} = \frac{1}{2}\begin{bmatrix} 1 & q \\ -q & 1 \end{bmatrix} v_{\alpha\beta} \qquad (9)$$

$$|v^{+}| = \sqrt{(v_\alpha^{+})^2 + \left(v_\beta^{+}\right)^2} \qquad (10)$$

$$|v^{-}| = \sqrt{(v_\alpha^{-})^2 + \left(v_\beta^{-}\right)^2} \qquad (11)$$

1) Balanced Systems

Analyzing the Fig. **7**, in a balanced three-phase system, we found that the magnitude of the positive component of αβ is constant and equal to the peak value of V_α and V_β, and the magnitude of the negative component of αβ is void.

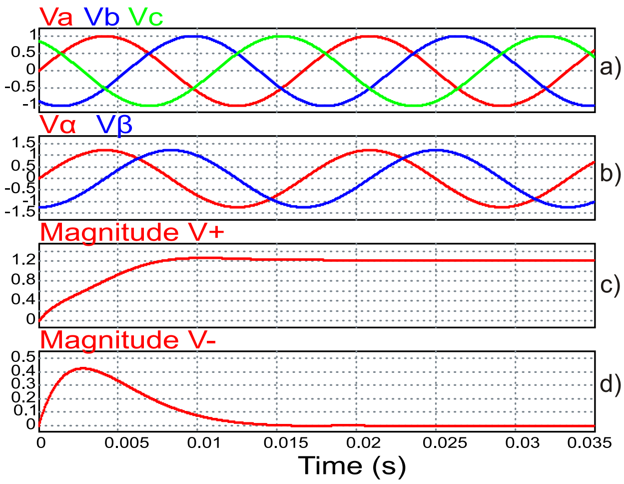

Fig. 7: Balanced System: a) $\boldsymbol{V_{abc}}$; b) $\boldsymbol{V_{\alpha\beta}}$; c) Positive component; d) Negative component.

2) Unbalanced Systems

But in unbalanced three-phase systems, as shown in Fig. **8**, we found that the magnitude of the positive component of αβ is also constant, but is different from the peak value $V_\alpha$and V_β, and the magnitude of αβ negative component is non-zero.

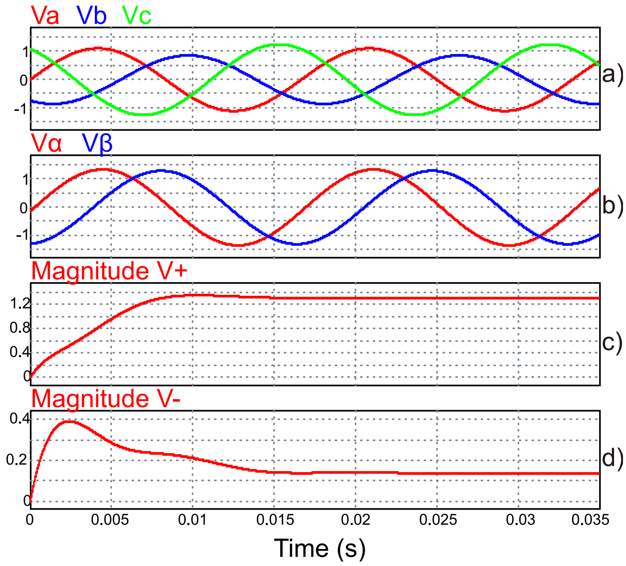

Fig. 8: Unbalanced System: a) $\boldsymbol{V_{abc}}$; b) $\boldsymbol{V_{\alpha\beta}}$; c) Positive component; d) Negative component

2. SOGI as Passive Methods Fault Detection

A passive methods use only currents and voltages sensors to detect any kind of disturbs in electrical system. Among the items examined for disturbances detection, we can highlight:

- Amplitude voltage flutuation;
- Frequency voltage flutuation;
- Phase voltage changing;

A. SOGI

The Second Order Generalized Integrator (SOGI) (P. Rodriguez, 2006) is used to filter of a signal at a particular frequency, eliminating all the harmonics. Moreover, it provides the same signal lagged 90°, needed for the calculation of positive and negative symmetrical components, as (**10**) and (**11**). The SOGI transfer functions are given by (**12**), (**13**), (**14**). Fig. **9** shows the SOGI block diagram. One can see that this diagram uses only simple arithmetic operations such as addition, subtraction and multiplic (P. Rodriguez, 2006)ation, and can be easily implemented on microcontrollers. For the SOGI work with maximum accuracy, it is necessary to know the exact angular frequency (ω) of the signal to be analyzed.

$$SOGI(s) = \frac{v'}{k\varepsilon_v}(s) = \frac{\omega' s}{s^2 + \omega^2} \tag{12}$$

$$D(s) = \frac{v'}{v}(s) = \frac{k\omega' s}{s^2 + k\omega' s + \omega^2} \tag{13}$$

$$Q(s) = \frac{qv'}{v}(s) = \frac{k\omega^2}{s^2 + k\omega' s + \omega^2} \tag{14}$$

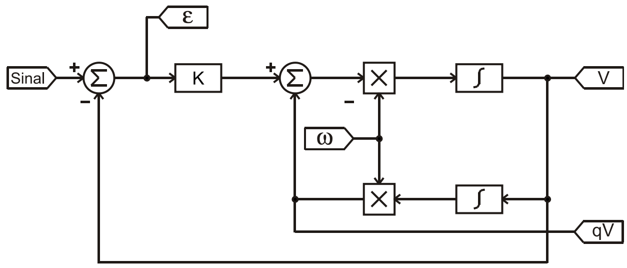

Fig. 9: Second Order Generalized Integrator (SOGI)

B. FLL

The FLL (Frequency Lock Loop) detects the fundamental frequency of the signal, making a feedback on SOGI in order that a small variation in this frequency does not affect your performance. In Fig. **10** is presented a FLL where we have as reference input a αβ three-phase decomposition of an ABC system.

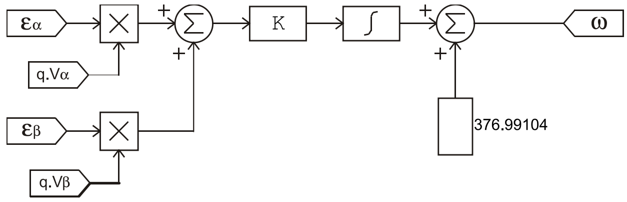

Fig. 10: Frequency Lock Loop (FLL).

C. Double SOGI-FLL

The Double SOGI proposed in [], and shown in Fig. **11** is a composite of two SOGIs and one FFL. The SOGIs filter the signals α and β, and generate the quadrature signals q.α and q.β to calculate a positive and negative symmetrical transformed. The FLL uses the signals α and β for the calculation of its fundamental frequency and feeds the two SOGIs.

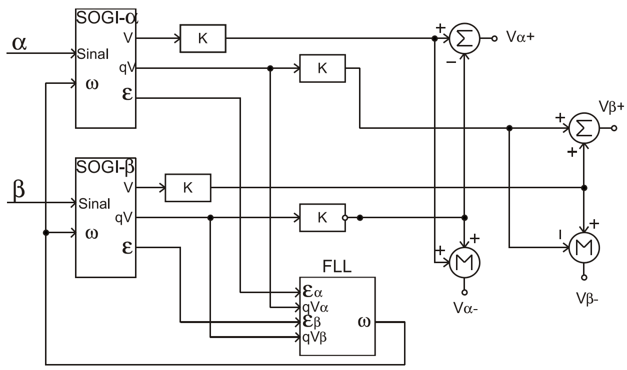

Fig. 11: Double SOGI-FLL

4. Simulating Faults in Three-Phase Systems

A. Situation of Normality

In order to make a simulation as close as possible to reality, and after a detailed analysis of the rules of ANEEL (Prodist, 2010), for systems under normal conditions, we consider the existence of maximum allowable harmonic distortion, distributed proportionally to ceilings provided for each order, as shown in Table **1**.

Table 1: Harmonic distortion in simulation

Order	%Harmonic		Order	%Harmonic
2	0.5		11	1.0
3	1.3		12	0.2
4	0.3		13	0.8
5	1.5		15	0.2
6	0.2		17	0.5
7	1.3		19	0.4
8	0.2		21	0.2
9	0.4		23	0.4
10	0.2		25	0.4

B. Fault Situation

For the simulation of disturbance, the occurrence of minor impact was used, and that the short circuit of one phase of the system with the ground.
For the analysis of perturbations, we analyze the following graphics:

1) Magnitude of αβ positive symmetric components $\left(\sqrt{V_{\alpha+}^2 + V_{\beta+}^2}\right)$;
2) Magnitude of αβ negative symmetric components $\left(\sqrt{V_{\alpha-}^2 + V_{\beta-}^2}\right)$;;
3) Angular frequency (ω);
4) Magnitude of the αβ phase error $\left(\sqrt{\varepsilon_{\alpha(f)}^2 + \varepsilon_{\beta(f)}^2}\right)$;
5) Magnitude of αβ vector components $\left(\sqrt{V_\alpha^2 + V_\beta^2}\right)$;
6) *d* synchronous vector component (V_d);
7) *q* synchronous vector component (V_q).

The sensitivity of the fault detection system is defined by the block shown in Fig. **12**, where the maximum permitted variations of the signals are determined.

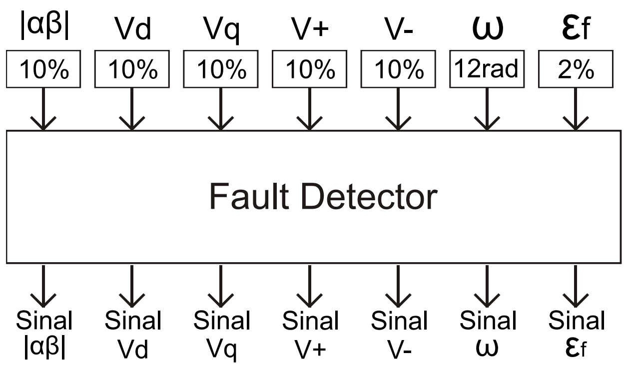

Fig. 12: Block diagram for calibration of the sensitivity of the fault detection.

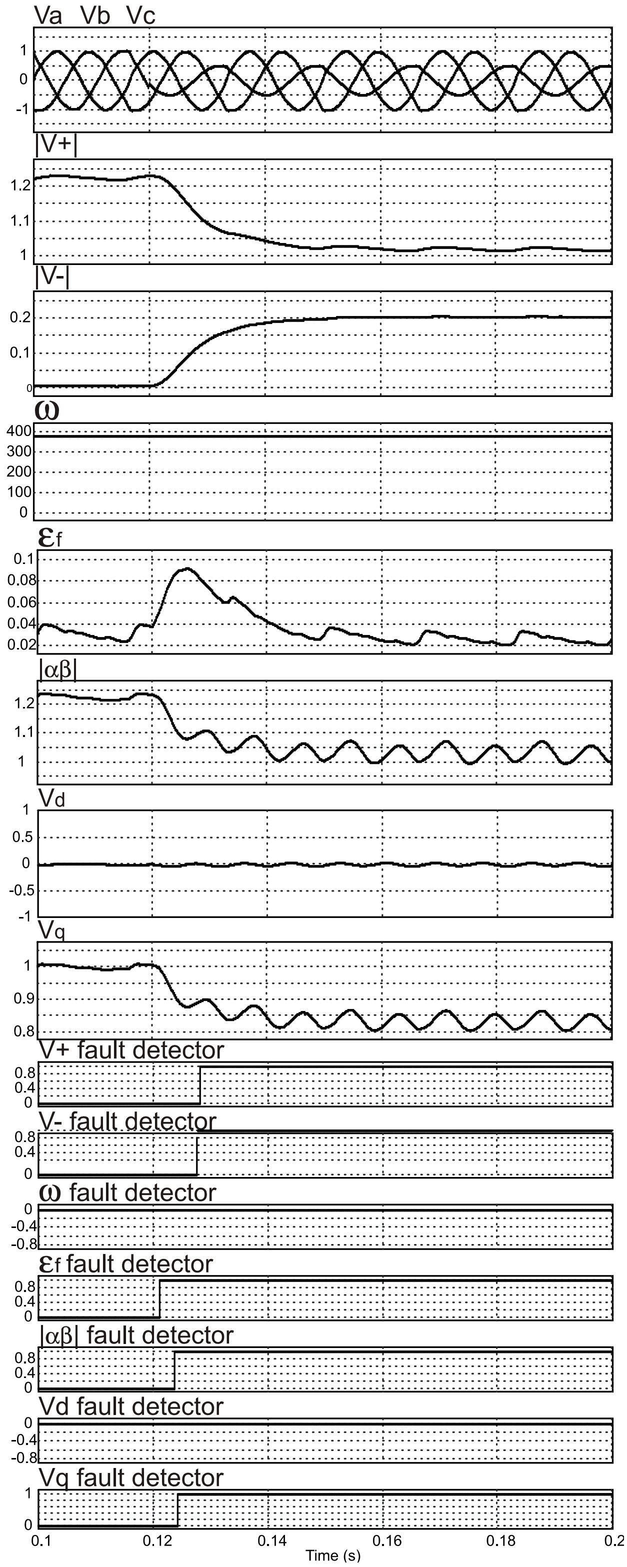

Fig. 13: Phase-Ground short circuit simulation.

6. Further Information

Questions concerning the preparation of papers may be addressed to the International Secretariat:

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7. Conclusions

A detailed study of the three-phase transforms vector was performed in order to elucidate their behavior, with disturbances in electrical three-phase system. It was studied, the algorithms listed below:

1. Clarke Transforms (αβ);
2. Park Transforms (dq);
3. Symmetrical components of αβ.

A comparative study between existing mathematical tools for three-phase systems was carried out, taking the development of highly accurate algorithms for detecting faults.

The possibility of adjusting the detection sensitivity of each method independently ensures reliability of used algorithms.

The algorithms presented in this paper were generated in Matlab and PowerSim environments, and they can be easily implemented in microcontrollers to be used in embedded systems.

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