A Positive and Negative Sequences Detecting Method Based on an Improved PQ Theory for Power Grid Synchronization

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Abstract

This paper proposes a modified PQ theory for detecting the positive and negative components of the utility voltages under faulty grid conditions. Fast and exact detecting of those sequences is important to achieve the operating at unity power factor integration of distributed generations into the main grid and for other uses. A detailed description of the proposed method has been accomplished. A phase locked-loop on synchronous rotating frame (SRF PLL) is commonly used to detect the exact phase angle; nevertheless this solution failed immediately to extract the two sequences under unbalanced and distorted conditions. The FMV filter constitutes a very interesting alternative to obtain the phase angle precisely and instantaneously; in this way, different kind of filters with a narrow bandwidth have been used for the separation of positive and negative components; however the response time is extended and an important phase delay is generated. the calculation of the mean value of the instantaneous power is a way to eliminate the AC component with a time response less than one of half of period. The obtained simulation results have been confirmed experimentally using a Dspace 1104 platform.

1. Introduction

Nowadays, the power networks suffers from various kind of problems as harmonics, flickers, sag/swell voltages, voltage distortion caused by electric and electronic equipment. For that reasons, an effective solution must be suggested to ensure the safety operating conditions of the power distribution networks. According to different survey studies, approximately 92% of the interruptions in industrial installations are voltage sag, or short-duration voltage sags [1], in particular, cause diverse operation shreddings [2], A common solution to this problem is to serve the electronic controller with a constant-voltage transformer or other mitigating device to provide adequate voltage to the controller or contactors/relays during the sag. In three-phase applications, the requirement of the positive and negative voltage sequences can contribute in the well operation of grid-connected power electronic systems such as Dynamic voltage restorer [3], power quality conditioners [4]-[5], uninterruptible power supplies . . . etc.

Variety of synchronization methods have been proposed and discussed during the recent years; PLLs are the most used [6]-[7]; however they have a large time response if they designed to operate under distorted or unbalanced voltages [8]. In [9]-[10] authors classified the widely used methods for real-time detections of the harmonics and reactive components into three types: The first one is based on the principal of the instantaneous active and reactive powers theory; referring to them it can just used to detect the harmonics currents. The second type is an adaptive detecting method [11] which was originally presented for a single phase and it could be extended to three phases systems; this type is based on the Notch filters; it can used for currents or voltages cases but it cannot separate the positive voltage component from the negative one.

In this paper a modified PQ theory is presented and applied in order to separate the positive component from the negative one. To avoid the phase delay and the large time response, no filters are needed to eliminate the alternative power component. So, the AC components of the positive and negative sequences are automatically canceled by the computation of the instantaneous active and reactive powers mean values with a time response less than one of half of period. The sine and cosine angles values required for the instantaneous powers calculation are directly provided by a FMV filter for both sequences.

2. System configuration

2.1. The three phase unbalanced voltages

The real three phase voltages could be expressed as:

$$\begin{cases} v_{sa} = v_{sa}^{+} + v_{sa}^{-} \\ v_{sb} = v_{sb}^{+} + v_{sb}^{-} \\ v_{sc} = v_{sc}^{+} + v_{sc}^{-} \end{cases} \tag{1}$$

where $v_{sa}^{+}, v_{sb}^{+}, v_{sc}^{+}$ and $v_{sa}^{-}, v_{sb}^{-}, v_{sc}^{-}$ are to the three positive and negative sequences componnets respectively, whereas:

$$\begin{cases} v_{sa}^{+} = \sum_{h=1}^{\infty} V_h^{+} sin(h\omega t + \phi_h^{+}) \\ v_{sb}^{+} = \sum_{h=1}^{\infty} V_h^{+} sin(h\omega t + \phi_h^{+} - \frac{2\pi}{3}) \\ v_{sc}^{+} = \sum_{h=1}^{\infty} V_h^{+} sin(h\omega t + \phi_h^{+} + \frac{2\pi}{3}) \end{cases} \tag{2}$$

$$\begin{cases} v_{sa}^{-} = \sum_{h=1}^{\infty} V_h^{-} sin(h\omega t + \phi_h^{-}) \\ v_{sb}^{-} = \sum_{h=1}^{\infty} V_h^{-} sin(h\omega t + \phi_h^{-} + \frac{2\pi}{3}) \\ v_{sc}^{-} = \sum_{h=1}^{\infty} V_h^{-} sin(h\omega t + \phi_h^{-} - \frac{2\pi}{3}) \end{cases} \tag{3}$$

In relations (2) and (3), V_h^{+}, ϕ_h^{+},V_h^{-}, ϕ^{-} denote the amplitude and the angle phase of the h^{th} harmonic component of positive and nigative sequences respectively.

2.2. The Filter Multi-Variable (FMV)

Hong-scok Song had defined the equivalent transfer functions of the integration in the synchronous references frame as [13]:

$$V_{xy}(t) = e^{j\omega t} \int e^{-j\omega t} U_{xy}(t) dt \tag{4}$$

The Laplace form of relation (4) is expressed by:

$$H(s) = \frac{V_{xy}(s)}{U_{xy}(s)} = \frac{s + j\omega_c}{s^2 + \omega_c^2} \quad (5)$$

In [14] authors had introduced a constant K in the transfer function H(s) to obtain the FMV with a cut-off frequency, so the previous transfer function H(s) becomes:

$$H(s) = k\frac{(s+k) + j\omega_c}{(s+k)^2 + \omega_c^2} \quad (6)$$

Now it is clear that the FMV is similar to other filters like high Pass-filter or low Pass-filter with a cut-off frequency ω_c and a gain k.

After some simplifications the following expressions could be obtained:

$$\begin{cases} \tilde{x}_\alpha(s) = \dfrac{k(s+k)}{(s+k)^2+\omega_c^2}x_\alpha(s) - \dfrac{k\omega_c}{(s+k)^2+\omega_c^2}x_\beta(s) \\ \tilde{x}_\beta(s) = \dfrac{k(s+k)}{(s+k)^2+\omega_c^2}x_\beta(s) + \dfrac{k\omega_c}{(s+k)^2+\omega_c^2}x_\alpha(s) \end{cases} \quad (7)$$

The scheme relative to the algorithm based on the FMV is shown in Fig. 1.

With the FMV filter the phase angle is obtained instantaneously without any time delay. The division of the $\alpha\beta$ voltages values by their amplitudes gives a synchronized sine and cosine signals with the desired component signal (Fig. 2).

2.3. The positive/negative sequence voltage detection

In this part the three phase voltages in the abc coordinates are transformed to the $\alpha\beta$ coordinates, then the PQ theotry is applied to compute the instantaneous active and reactive powers; however the $\alpha\beta$ current components are substitued by the sine and cosine signals delivred by the FMV filter. So, in $\alpha\beta$ reference frame the voltage components are given by :

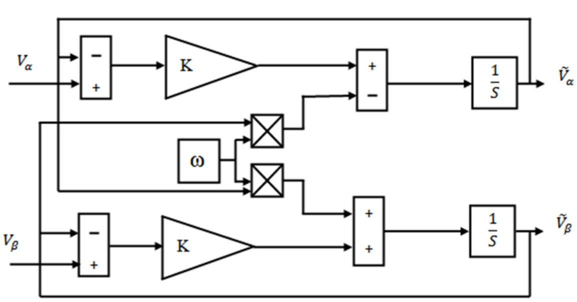

Figure 1. FMV filter used for generating Sine and Cosine signals.

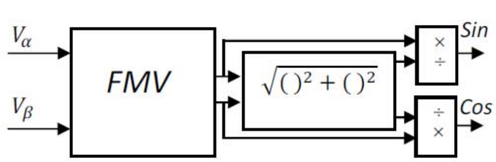

Figure 2. The Sine and Cosine signals obtained using the FMV filter.

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad (8)$$

Under umbalanced voltages conditions $v_{s\alpha}$ and $v_{s\beta}$ contain both the positive and negative sequences (v_α^+, v_β^+), (v_α^-, v_β^-) respectively. Theses components are expressed as:

$$\begin{cases} v_\alpha^+ = \sqrt{\frac{3}{2}}\sum_{h=1}^{\infty} V_h^+ sin(h\omega t + \phi_h^+) \\ v_\beta^+ = -\sqrt{\frac{3}{2}}\sum_{h=1}^{\infty} V_h^+ cos(h\omega t + \phi_h^+) \end{cases} \quad (9)$$

$$\begin{cases} v_\alpha^- = \sqrt{\frac{3}{2}}\sum_{h=1}^{\infty} V_h^- sin(h\omega t + \phi_h^-) \\ v_\beta^- = \sqrt{\frac{3}{2}}\sum_{h=1}^{\infty} V_h^- cos(h\omega t + \phi_h^-) \end{cases} \quad (10)$$

The calculation of of the component p and q by the formula of the instantaneous power components gives us :

$$\begin{bmatrix} p^+ \\ q^+ \end{bmatrix} = \begin{bmatrix} sin(\omega t+\phi) & -cos(\omega t+\phi) \\ cos(\omega t+\phi) & sin(\omega t+\phi) \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} p^- \\ q^- \end{bmatrix} = \begin{bmatrix} sin(\omega t+\phi) & cos(\omega t+\phi) \\ -cos(\omega t+\phi) & sin(\omega t+\phi) \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (12)$$

$$\begin{aligned} p^+ &= \sqrt{\frac{3}{2}}V_1^+ cos(\phi_1^+ - \phi) \\ &+ \sqrt{\frac{3}{2}}\sum_{h=2}^{\infty} V_h^+ cos((h-1)\omega t + \phi_h^+ - \phi) \\ &- \sqrt{\frac{3}{2}}\sum_{h=1}^{\infty} V_h^- cos((h+1)\omega t + \phi_h^- + \phi) \end{aligned} \quad (13)$$

$$\begin{aligned} q^+ &= \sqrt{\frac{3}{2}}V_1^+ sin(\phi_1^+ - \phi) \\ &+ \sqrt{\frac{3}{2}}\sum_{h=2}^{\infty} V_h^+ sin((h-1)\omega t + \phi_h^+ - \phi) \\ &+ \sqrt{\frac{3}{2}}\sum_{h=1}^{\infty} V_h^- sin((h+1)\omega t + \phi_h^- + \phi) \end{aligned} \quad (14)$$

$$\begin{aligned} p^- &= \sqrt{\frac{3}{2}}V_1^- cos(\phi_1^- - \phi) \\ &+ \sqrt{\frac{3}{2}}\sum_{h=2}^{\infty} V_h^- cos((h-1)\omega t + \phi_h^- - \phi) \\ &- \sqrt{\frac{3}{2}}\sum_{h=1}^{\infty} V_h^+ cos((h+1)\omega t + \phi_h^+ + \phi) \end{aligned} \quad (15)$$

$$\begin{aligned} q^- &= -\sqrt{\frac{3}{2}}V_1^- sin(\phi_1^- - \phi) \\ &- \sqrt{\frac{3}{2}}\sum_{h=2}^{\infty} V_h^- sin((h-1)\omega t + \phi_h^- - \phi) \\ &- \sqrt{\frac{3}{2}}\sum_{h=1}^{\infty} V_h^+ sin((h+1)\omega t + \phi_h^+ + \phi) \end{aligned} \quad (16)$$

From (13), (14), (15) and (16) it is clear that each formula has a continues part and an alternative one. The standard PQ theory uses a second low pass filter or a second high pass filter to cancel the alternative component which correspond to harmonics or to the negative system generated in the unbalanced voltages cases.

As it is mentioned above, the use of filter is not suitable in the fast transient phenomenon because it causes an inherent large time response. To overcome this problem, our idea consists in calculating in real time the average signal value in order to eliminate the alternative component; this is will be accomplished less than a half of period.

$$< y >= \frac{1}{T} \int_{t_o}^{t_o+T} y(t)dt \tag{17}$$

The positive and negative voltages are then defined respectively by:

$$\begin{bmatrix} v_\alpha^p \\ v_\beta^p \end{bmatrix} = \begin{bmatrix} sin(\omega t + \phi) & cos(\omega t + \phi) \\ -cos(\omega t + \phi) & sin(\omega t + \phi) \end{bmatrix} \begin{bmatrix} < p^+ > \\ < q^+ > \end{bmatrix} \tag{18}$$

$$\begin{bmatrix} v_\alpha^n \\ v_\beta^n \end{bmatrix} = \begin{bmatrix} sin(\omega t + \phi) & -cos(\omega t + \phi) \\ cos(\omega t + \phi) & sin(\omega t + \phi) \end{bmatrix} \begin{bmatrix} < p^- > \\ < q^- > \end{bmatrix} \tag{19}$$

Finally, it is easy to obtain the positive and negative voltages along the abc axes by the inverse transformation of Concordia:

$$\begin{bmatrix} v_{sa}^p \\ v_{sb}^p \\ v_{sc}^p \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_\alpha^p \\ v_\beta^p \end{bmatrix} \tag{20}$$

$$\begin{bmatrix} v_{sa}^n \\ v_{sb}^n \\ v_{sc}^n \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_\alpha^n \\ v_\beta^n \end{bmatrix} \tag{21}$$

where:

$$\begin{cases} v_{sa}^p = V_1^+ sin(\omega t + \phi_1^+) \\ v_{sa}^n = V_1^- sin(\omega t + \phi_1^-) \end{cases} \tag{22}$$

3. Simulation results

A balanced three phase voltages source is used to feed a three phase rectifier converter connected to a resistive load. The unbalanced system voltages is intentionally created by a sudden inserting of series resistances with two different phases. Fig. 3 illustrates the proposed structure scheme. Figure 3 shows the three phase voltages zoomed around t=6.37s to t=6.65s where the unbalance on the voltage source is created by the introduction of resistances and also the angle phase.

Figures 4 and 5 show the effectiveness of the proposed method in extraction of the positive and the negative sequences.

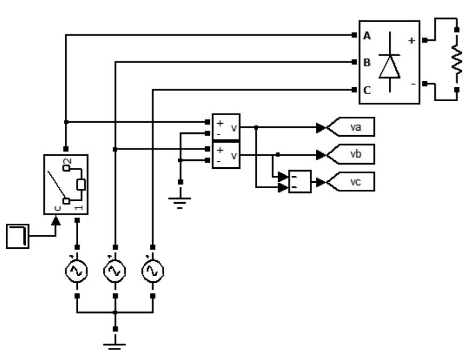

Figure 3. The unbalanced voltages structure simulated.

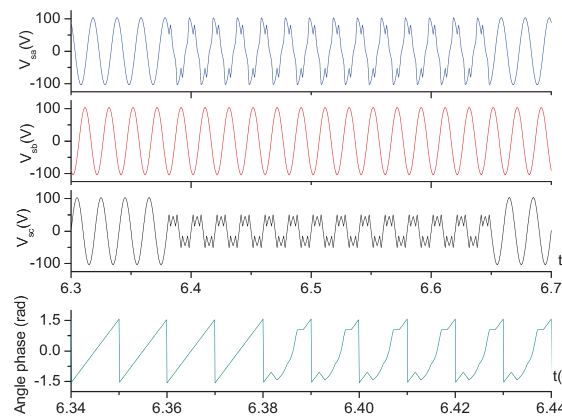

Figure 4. Simulation results. The unbalanced voltages simulated and their phase angle

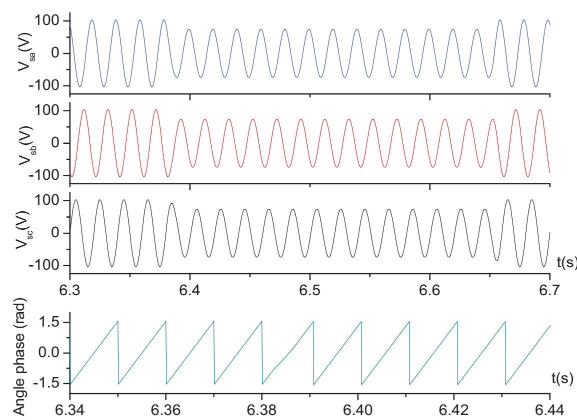

Figure 5. Simulation results. The extracted direct voltages and their phase angle.

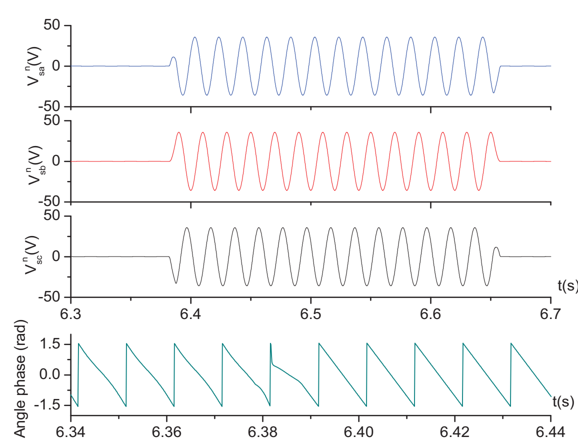

Figure 6. Simulation results. The extracted inverse voltages and their phase angle.

4. Experimental validation

The simulation results have been well validated experimentally using Dspace 1104 platform.

Figure 8 shows the waveform of the three line voltages under the unbalance considered. It can be seen that the phase angle of the three line voltages have been changed since the series resistances are introduced to create unsymmetrical voltages at t=6.37s.

We notice from Fig .9 and fig.10 that the proposed method does well in experiment as well in simulation; both positive and negative sequences are obtained with a good performance in detection of each sequence.

The last experimental results, shows the amplitudes of the positive and negative line voltages, it is obviously remarkable that the proposed strategies used in this paper present good performance.

To evaluate the performance of the classical PQ filters used for canceling the alternative components, a second low pass filter is used in comparison with the calculation of mean values. The obtained results are shown in Fig. 6 where we can noticed that the classical PQ method using LPF failed in extracting the positive and negative sequences of the main voltage.

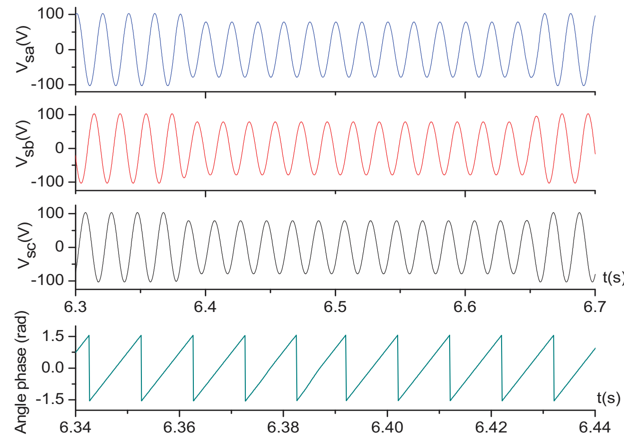

Figure 9. Experimental results. The extracted direct voltages and their phase angle.

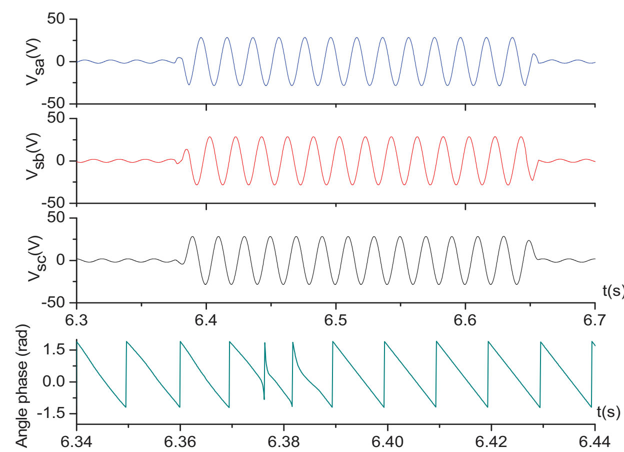

Figure 10. Experimental results. The extracted inverse voltages and their phase angle.

Figure 7. Experimental setup used.

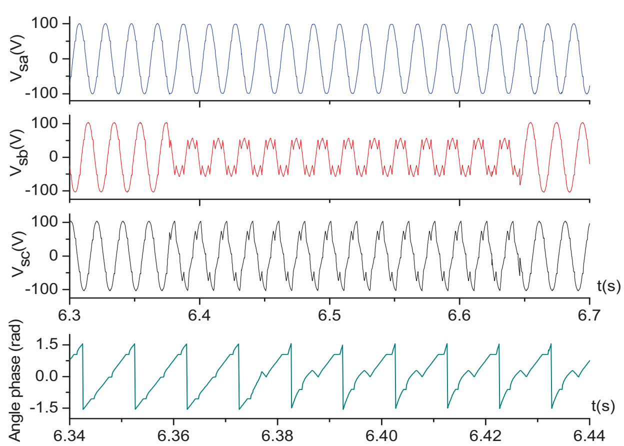

Figure 8. Experimental results. The unbalanced voltages simulated and their phase angle.

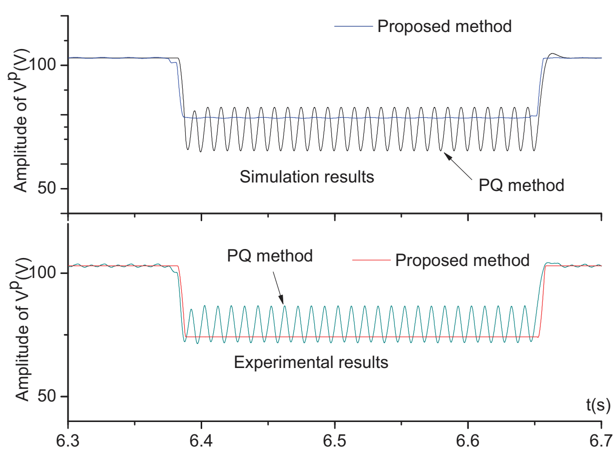

Figure 11. The amplitude of the direct component obtained by the proposed method and the classical PQ. Top simulation results and bottom experimental ones.

5. Conclusion

In this paper a modified PQ theory is presented in order to detect the positive and the negative voltage sequences under unbalanced conditions. The cancellation of the ripple components is done by calculating online the mean value of each desired quantity to avoid the large time response caused by the narrow bandwidth filters commonly used. To avoid an additional time delay response, a FMV filter is used to obtain synchronized components instead of using the well known PLL solution.

The simulation and experiment results present the effectiveness of the proposed method.

6. References

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