An Improved Technique for the Estimation of Local Frequency, Fundamental Component Phasor and Instantaneous Symmetrical Components

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Abstract. Fundamental component estimation, including its phase and amplitude information along with instantaneous fundamental symmetrical components, is of great importance for grid connected power electronics converters control, namely in power conditioning applications such as Dynamic Voltage Restorers (DVRs) and Unified Power Flow Controllers (UPFCs). Several methods have been proposed to estimate these parameters recently, particularly digital ones. The developments of new and more efficient microprocessor-based relays and supervising and monitoring systems have given support to those estimation methods. In this paper, an adaptive FIR filter based method for fundamental component estimation is used as support for a new proposed method. It enables fundamental component phasor, frequency and instantaneous fundamental symmetrical components estimation based on the grid voltage fundamental component. The method is tested under typical grid perturbations and is compared with two high performance alternative methods through objective and quantitative criteria.

Keywords

Power quality, Voltage distortion, Symmetrical components, Frequency estimation

1. Introduction

In power systems, the use of microprocessor-based control systems and relays allows the implementation of state estimation, control and protection functions through software. Comparatively with electromechanical and solid-state relays and control systems they have as main advantages: lower cost, additional functions like communications, parameterization, self-test, self-monitoring, diagnostics, reduced space and simplified instrumentation through software integrated functions, [1].

The increasing of real-time signal processing capacity of microprocessor-based platforms has allowed the development of several numerical methods for the estimation of grid voltage parameters like phasor, frequency, instantaneous and stationary symmetrical components, etc.

Grid voltage amplitude detection has application in protection relays, automatic voltage regulators, UPS's, etc.

Grid connection of power electronics converters implies the knowledge of grid voltage phase. These applications have increased with the following objectives: power conditioning, with static compensators and other FACTS devices; distributed energy generation, with solar and wind energy sources. Also, there are conventional applications like controlled rectifiers and UPS's.

Frequency estimation is necessary to a stable, secure and efficient grid operation; its value represents the dynamic balance between energy generation and load consumption. It is required to an effective active power control, load shedding, generator protection and synchronization, [2].

The fundamental component is necessary to the control and assessment of power quality. Different processing methods of grid voltage waveform parameters require a free of perturbations fundamental component detection.

Symmetrical stationary components knowledge allows grid unbalance quantification and failure detection. Instantaneous symmetrical components are the basis for signal generation for compensating dynamic unbalances, [3]. They are also used in grid synchronization and digital protection relays. In this paper, the proposed method is focussed in grid unbalance compensation.

Generally, the proposed methods (digital filters, discrete Fourier transform, Kalman filters, phase-locked loop, weighted least squares, etc) for estimating these parameters present performance degradation under grid voltage distortion: harmonics, sub-harmonics, noise, amplitude, phase and frequency deviations, notches, swells, unbalances, etc. The results obtained and presented in different publications do not clarify the operation under a systematic set of conditions; there is no agreement about the best performance.

In this paper it is presented a method for phasor fundamental component estimation, from which it is obtained the positive sequence instantaneous fundamental symmetrical component and the grid frequency, with application in power conditioning systems. The phase estimation is based on orthogonal band-pass filters, with the cosine filter replaced by a quadrature phase shifting module which implements an instantaneous rotation of the filtered fundamental component. The filter is an adaptive band pass one with no delay.

The proposed method performance is compared under objective and quantitative criteria, with two of the most used alternative methods.

2. Parameters Estimation with the EPLL and DFT Methods

A. Enhanced Phase-Locked-Loop (EPLL)

The Phase-Locked Loop (PLL) is one the traditional methods to synchronize power converters to the grid. The conventional approach to implement a PLL structure consists in estimating the difference between the input and output signals. The EPLL structure directly estimates the input signal fundamental component phase through a phase detector, [3]. This signal is filtered by a loop filter in order to eliminate distortions and is the input of a voltage-controlled oscillator whose output is a signal synchronous to the input signal.

In the EPLL structure, the upgrade from a proportional gain controller to a proportional plus integral one allows frequency estimation. The EPLL processing gives in real time: amplitude, angular frequency, and fundamental component total phase. This processing can be translated to a first order discrete model with three internal parameters, dimensioned considering the sampling period. They contribute to the convergence process and allow adjusting amplitude, frequency and phase estimation, [3].

B. Discrete Fourier Transform (DFT)

The need for fast dynamics in power systems related processes imposed DFT calculations with a single data window with a duration of typically one grid period.

To avoid phase differences between input and output signals, and spectral leakage in case of frequency deviation from the nominal value, some DFT evolutions are known: adaptive change of the sampling period, to become a sub-multiple of the grid period; phase correction; and adaptive change of the window data length. The last two are preferable since they do not require frequency execution adjustment of the DFT algorithm, possibly an embedded algorithm with others that need to be executed at a fixed frequency.

When the grid frequency has a different value from the nominal the sampling process is asynchronous; the sampling signal is not synchronized to the grid voltage, thus originating the referred errors. A recursive DFT method with analytical phase and amplitude correction has been proposed in [4]. The method's precision and simplicity is a consequence of the frequency deviation estimation process and the adaptive algorithm for harmonics effects suppression. It will be used for comparative analysis.

For a higher precision, but also with more computational effort, the analytical phase and amplitude correction stage can be replaced by an absolute DFT recalculation with the more recent synchronous window data, as in (1):

$$\mathbf{X}^h[k] = \frac{2}{M}\sum_{n=0}^{M-1} x[k-n]e^{-j\left(\frac{2\pi}{M}\right)nh} \tag{1}$$

being h the harmonic order, k the actual instant, and M the estimated synchronous window data length.

3. Improved Technique for Fundamental Component Phasor Estimation

The proposed method extracts the following parameters of the grid voltage fundamental component: amplitude, phase and frequency of the fundamental component, and fundamental instantaneous symmetrical components. The estimation method is based on the fundamental component and consists in four main functions: 1- multi-stage adaptive band-pass filter, 2- digital 90º phase shifter, 3- amplitude estimation and 4- phase and frequency estimation, as is represented in Fig. 1 and Fig. 2.

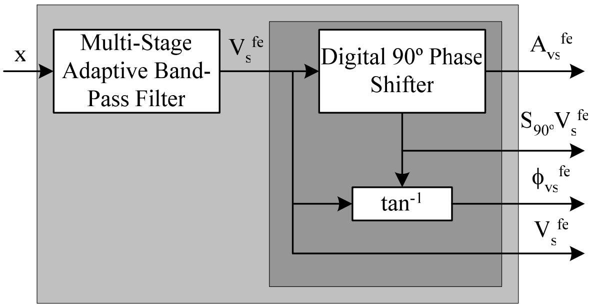

Fig. 1. Multi-stage adaptive band-pass filter and phasor estimation.

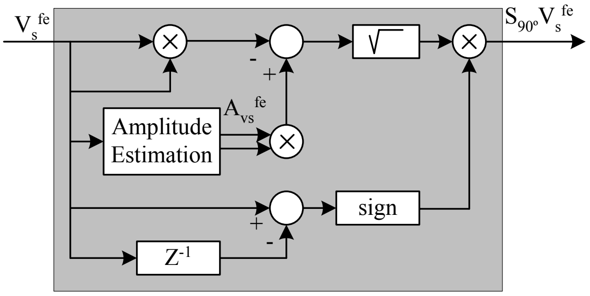

Fig. 2. Digital 90 degree phase-shifter and amplitude estimation.

A. Multistage Adaptive Band-Pass Filter (MABPF)

In [5] the fundamental component is extracted through an adaptive digital filter with the General Multiplicative Parameters method. It consists in adapting a FIR band pass filter by multiplying its coefficients by two adaptive parameters. It allows harmonics suppression, notches elimination and other grid perturbations attenuation even under off nominal frequency by robust filter adaptation. There is no relevant phase difference between filtered fundamental component and the input waveform.

The method consists in three stages: 1- median filter, to eliminate impulse type perturbations; 2- predictive adaptive band pass filter, to attenuate DC voltage and harmonics present in the input voltage; and the adaptive process, to compensate the two sampling intervals delay due to the median filter and the interpolator; and 3- the interpolator itself, to increase the filtered signal resolution in order to be used in the zero crossing detection.

In the output filter processing, $y[k]$, (2), $g1[k]$ and $g2[k]$ are the parameters to be adapted according to (3) and (4); $h[k]$ are the coefficients of the fixed FIR band pass filter; $x[k]$ are the grid voltage samples after being filtered by the median filter; Q is the number of filter coefficients; γ is the adaptive gain and $e[k]$ is the error.

$$y[k] = g_1[k]\sum_{n=0}^{Q/2-1} h[n]x[k-n] + g_2[k]\sum_{n=Q/2}^{Q-1} h[n]x[k-n], \quad (2)$$

$$g_1[k+1] = g_1[k] + \gamma e[k]\sum_{n=0}^{Q/2-1} h[n]x[k-n], \quad (3)$$

$$g_2[k+1] = g_2[k] + \gamma e[k]\sum_{n=Q/2}^{Q-1} h[n]x[k-n], \quad (4)$$

$$e[k] = x[k] - y[k-2], \quad (5)$$

A one to six, second order, Lagrange interpolator is used to support sinusoidal signals and minimizing the input waveform distortion, [5].

This process only estimates the fundamental component, not the phasor and neither the frequency, as is done by the EPLL and DFT methods. Also, it does not estimate the symmetrical components.

B. Fundamental Component Phasor and Frequency Estimation

The output of the adaptive filter is the instantaneous fundamental component almost free of grid perturbations. The digital 90° phase-shifter, shown in Fig. 2, allows the estimation of the fundamental component phase, which will be used in fundamental instantaneous symmetrical components determination.

The phase shifting, (6), is slightly based on a method proposed in [6], with some major changes.

$$S_{90^\circ} V_s^{fe}[k] = \pm\sqrt{\left(A_{vs}^{fe}[k]\right)^2 - \left(V_s^{fe}[k]\right)^2} \quad (6)$$

Due to the availability and low price of high performance DSP-based hardware, the square root is calculated in real-time, not implicitly, since the square root sign is obtained from the sign of the input signal derivative. Normalization is not implemented, being directly added the squared amplitude to the squared input signal. The amplitude estimation, (7), is based on a method proposed in [7], where T_s is the sampling period.

$$A_{vs}^{fe}[k] = \sqrt{\left(V_s^{fe}[k]\right)^2 + \left(\frac{V_s^{fe}[k-1] - V_s^{fe}[k]\cos(\omega_g T_s)}{\sin(\omega_g T_s)}\right)^2} \quad (7)$$

As is evident from (7), the amplitude estimation implies the knowledge of the grid angular frequency, ω_g. The proposed method uses a pre-estimation value obtained from the time interval between the two most recent positive zero crossings of the estimated fundamental component, Δt_{pzc}, (8):

$$f_{vs}^{pfe}[k] = \frac{1}{\Delta t_{pzc}} \quad (8)$$

The above frequency estimation has an error inversely proportional to the algorithm execution frequency, which determines the estimation precision of the zero crossing intervals measurement. With a 10 kHz sampling frequency the error in the pre-estimation stage varies between 0.10 and 0.15 Hz, for an input frequency range from 45 to 55 Hz.

Frequency estimation precision is highly improved in the final stage, from the variation of the phase angle between the actual phasor, k, and the phasor of a delayed data window, k-N, calculated with (9), being f_s the sampling frequency.

$$f_{vs}^{fe}[k] = \frac{\phi[k] - \phi[k-N]}{2\pi}\cdot\frac{f_s}{N} \quad (9)$$

The use of an N sample intervals delayed data window allows an increased precision but with slower dynamics. To decrease the susceptibility to grid disturbances the method can use a median filter with NF data values.

C. Fundamental Instantaneous Symmetrical Components Estimation

The proposed method estimates the fundamental component phasor, thus allowing stationary and instantaneous symmetrical components calculation needed for power conditioning applications, [8].

The determination of the positive sequence instantaneous ones ((10), (11) and (12)) implies the availability of the 90° phase shifted fundamental component, given by the S_{90} operator, as shown in Fig. 1. This operation is easily obtained through an instantaneous rotation of the fundamental component phasor, as explained above.

$$v_{sa}^{i+} = \frac{1}{3} v_a^f - \frac{1}{6}\left(v_b^f + v_c^f\right) - \frac{1}{2\sqrt{3}}\left(S_{90} v_b^f - S_{90} v_c^f\right), \tag{10}$$

$$v_{sc}^{i+} = \frac{1}{3} v_c^f - \frac{1}{6}\left(v_a^f + v_b^f\right) - \frac{1}{2\sqrt{3}}\left(S_{90} v_a^f - S_{90} v_b^f\right), \tag{11}$$

$$v_{sb}^{i+} = -v_{sa}^{i+} - v_{sc}^{i+} . \tag{12}$$

4. Tests and Results

The comparative analysis between the three methods should be done under the same test conditions, representative of the electrical grid, and with objective criteria. High performance and low cost hardware allow the use of a 10 kHz execution frequency in the presented algorithms. The EPLL parameterization is the one recommended in [3]. The DFT algorithm, for a 10 kHz sampling frequency and 50 Hz grid nominal frequency, uses a window length with 200 data samples.

The MABPF constituted by the median filter, the band-pass filter and adaptive process runs at 1.67 kHz; the interpolator, as the phase and frequency pre-estimation is executed at 10 kHz. The filter has Q=22 and γ=0.02. For a higher precision, the amplitude, phase and frequency estimation are synchronized to the MABPF at 1.67 kHz.

The input data to the amplitude estimation block, (6), is obtained at the input of the interpolator to avoid interpolating errors. Frequency estimation is made with N=100, i.e. with a half cycle delay, and a median filter with NF=17 data frequency values. The positive sequence instantaneous fundamental symmetrical components algorithm runs, in all methods, at 10 kHz.

Single and three-phase tests, under transient and steady-state operation have been done. The transient essays result from the application of step changes in one or more grid voltage parameters.

A. Single-Phase Tests

Step changes in the grid parameters include: amplitude, representing

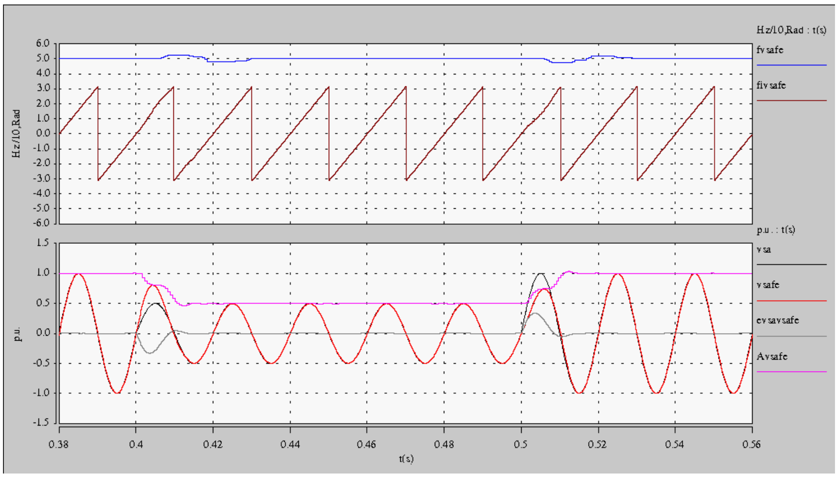

Fig. 3. Voltage sag response of the proposed method.

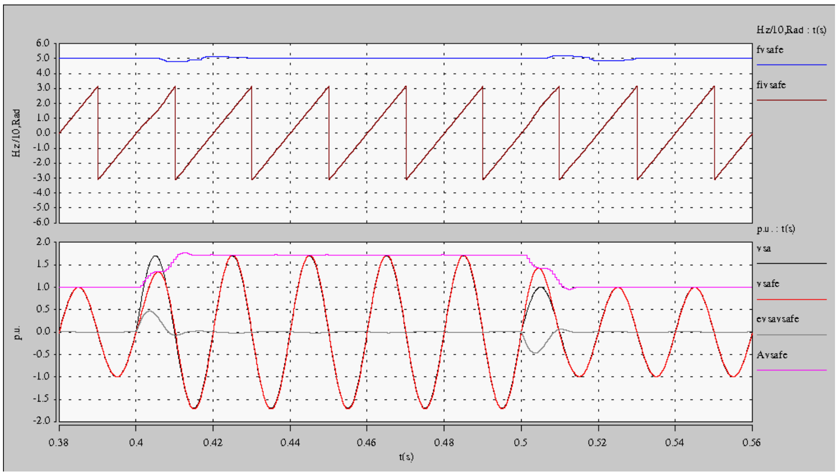

Fig. 4. Voltage swell response of the proposed method.

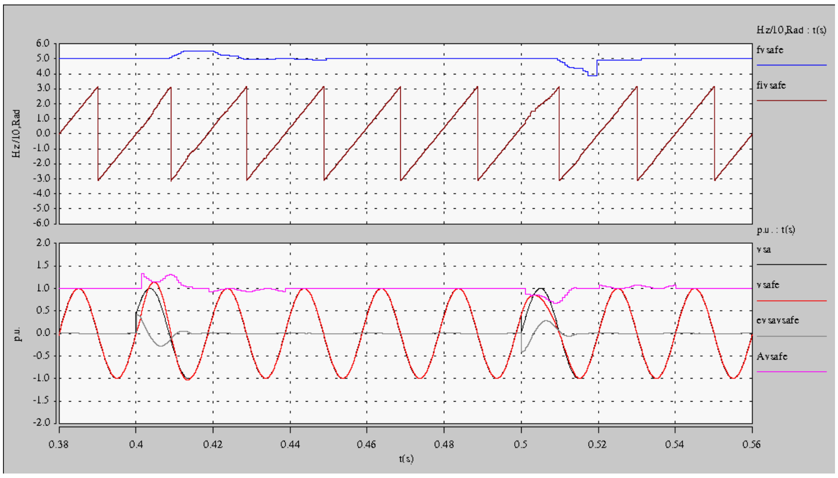

Fig. 5. Response under a phase step change in the input signal.

voltage sags (Fig. 3) and swells (Fig. 4), with 0.5 and 1.7 p.u. respectively; phase (Fig. 5), coming from the disconnection of parallel feeders or sudden load changes, with +25º followed by the reestablishment, -25º, after 100 ms. [Traces shown in Fig. 3, 4 and 5 are the estimated fundamental component (vsafe) (with MABPF), respective amplitude (Avsafe), phase (fivsafe) and frequency (fvsafe), also there are the grid voltage waveform (vsa), which is a pure sinusoidal wave, and the fundamental component estimation error (evsavsafe)].

The proposed estimation method (PM) has a very fast response to voltage sag (half cycle) and a good behaviour under a voltage swell. Also, in the phase change, the method is a fast one. Since the adaptive band-pass filter does not introduce any delay the frequency estimation converges in about 30 ms.

In strong grids the voltage waveform frequency must be comprised between 47 and 52 Hz and the maximum allowed frequency rate of change is 1 Hz/s.

Fig. 6 and Fig. 7 illustrate the performance of the proposed method for a +5 Hz frequency step and reestablishment, followed by a -5 Hz change. Parameters adaptation due to frequency variation is shown in Fig. 7, so reducing the error estimation in the filter output. In power systems real operating conditions there are no such frequency changes; the test just allows the assessment of the methods dynamics. [Traces in Fig. 6 are the real grid frequency (fvsa) and its estimated value (fvsafe); in Fig. 7 are the fundamental component estimation error (evsavsafe), the fundamental component amplitude estimation (Avsafe) and the multiplicative general parameters adaptation (g1a and g2a)].

Other important grid perturbations have been tested: AC voltage fluctuation, superimposing a sine wave voltage with amplitude of 0.3 p.u. and 10 Hz frequency (Fig. 8); additive Gaussian noise with a variance of 0.05, resulting from a very low signal to noise ratio of 10 dB (Fig. 9).

All perturbations appear during 100 ms being the IAE calculated in this interval. The later test allows comparing the methods precision, illustrated in Fig. 10 for the fundamental component amplitude and frequency estimation for the proposed method and the two reference methods (EPLL and DFT). The proposed method has higher noise immunity and a better performance in the precision and the harmonics and noise rejection tests, as demonstrated by the Integral of Absolute Error, IAE, (see Table I for a global comparison).

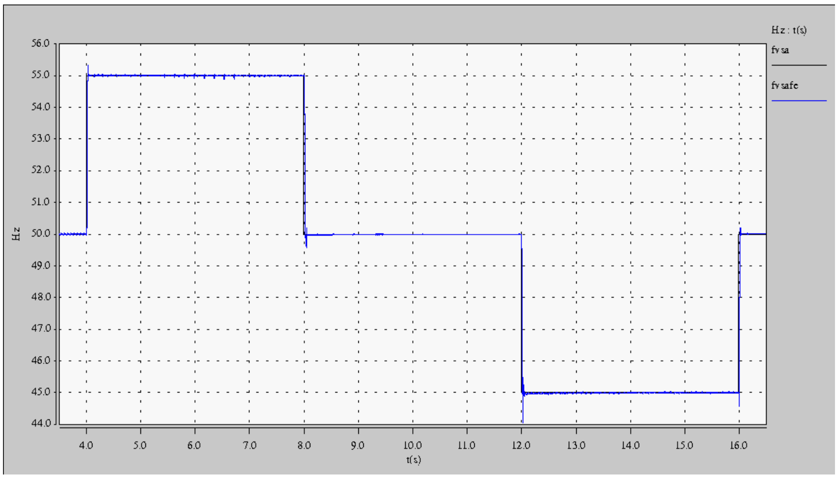

Fig. 6. Proposed method response to a frequency step change.

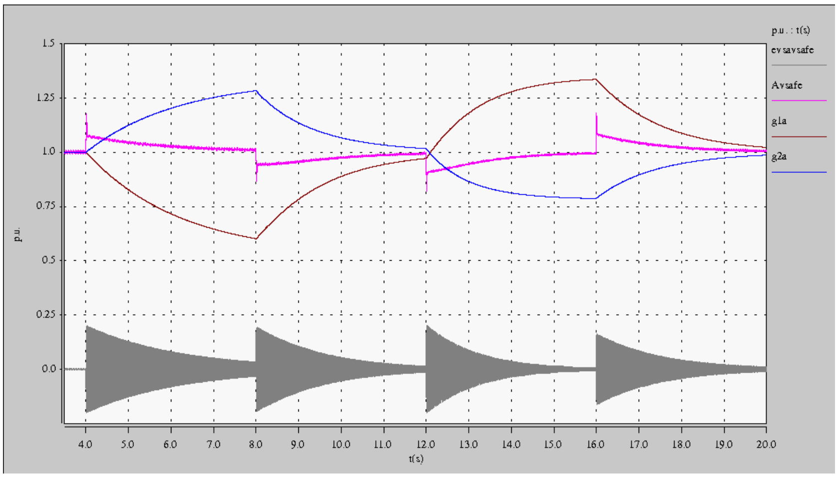

Fig. 7. Fundamental component error estimation and adaptive band-pass filter parameters adaptation corresponding to Fig. 6.

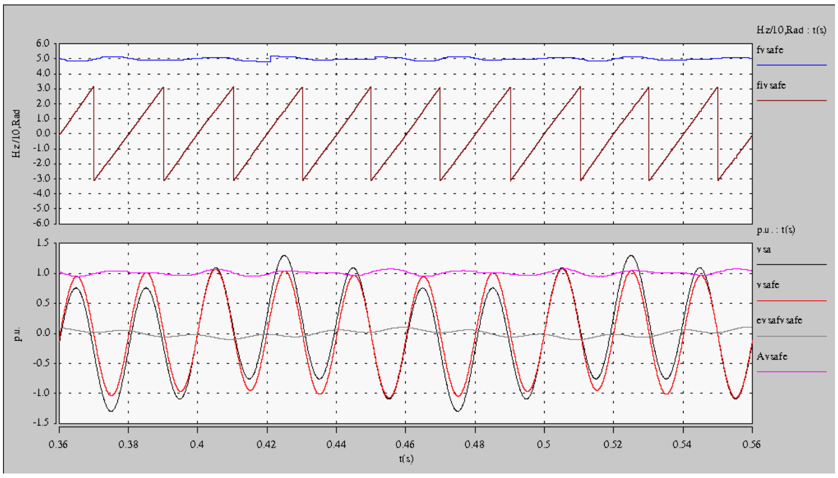

Fig. 8. Low frequency voltage fluctuation immunity.

B. Three-Phase Tests

To assess the estimation of the positive sequence fundamental instantaneous symmetrical component capability and the functionality under grid voltage unbalance several tests have been made: balanced three phase sag and swell, harmonics attenuation, and unbalance. Figure 11 shows the method's behaviour in the estimation of the positive sequence symmetrical component which, in balanced conditions, should be always equal to the grid voltage.

Immunity to harmonics perturbations has been tested by adding to the grid voltage homopolar harmonics with 0.3 p.u. for the 3rd harmonic with a phase of +50º relative to phase *a*, Fig 12. The method has high immunity to the 3rd harmonic since harmonic distortion is highly attenuated.

Two cases have been tested in the unbalanced condition: case 1 - amplitudes (*abc*) of 1.0, 0.1 and 0.5 and phases (*abc*) of +120º, -175º and 100º (Fig. 13), and case 2- amplitudes (*abc*) of 1.0, 0.5 and 0.5 and phases (*abc*) of -120º, -135º and 135º (not shown, but included in Table I for comparison purposes). The balanced condition is (*abc*): 1.0, 1.0 and 1.0 and 0º, -120º, +120º amplitude and phase, respectively. [Traces in Fig. 11 to 13 are the grid voltages (vsa, vsb, vsc) and the estimated fundamental instantaneous positive sequence (vsai+, vsbi+, vsci+)].

C. Comparative Analysis between the Three Methods

The comparative criterion for parameter step changes is the error settling time (ST), corresponding to the time elapsed until the error is limited to 2% of the grid voltage. The ST value is shown for the two transient conditions: initial step and reestablishment.

Immunity tests to stationary perturbations like voltage fluctuations, noise and harmonic pollution and noise with a finite duration, are characterized by the integral of the absolute error (IAE). For perturbations generating distortion the applied criterion is the total harmonic distortion (THD).

Systematic tests made with the three methods gave the results organized in Table I.

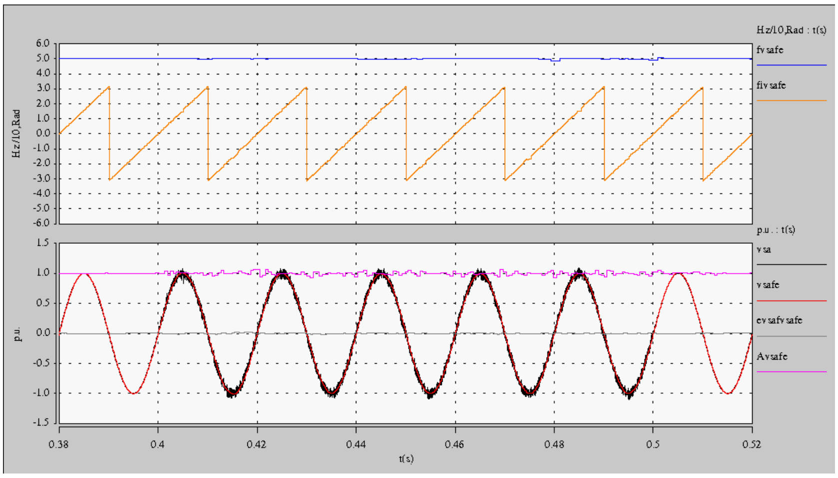

Fig. 9. Immunity to gaussian noise of the proposed method.

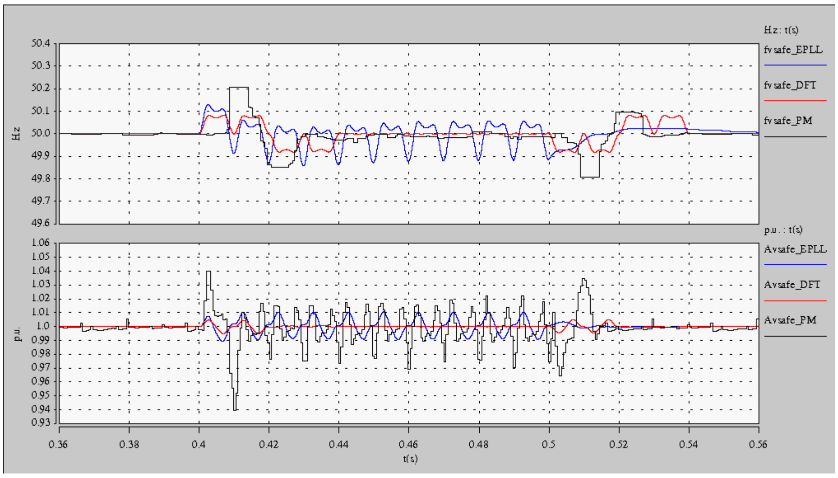

Fig. 10. Precision comparison between the three methods in the estimation of the fundamental component amplitude and frequency.

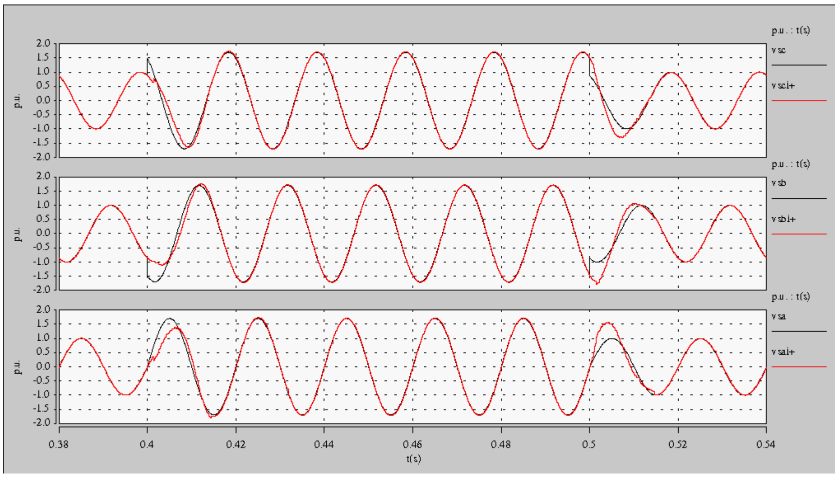

Fig. 11. Positive sequence fundamental instantaneous symmetrical component estimation during a three phase voltage swell.

In single or three phase operation, the proposed estimation method has a very fast response to voltage sags and a good behaviour under a voltage swell. Also, in the phase change, the method is a fast one. Harmonics and low frequency voltage fluctuations are efficiently rejected by the proposed method. Instantaneous symmetrical components during three-phase asymmetrical unbalances are also fast and correctly estimated.

5. Conclusion

Different power systems applications of power electronics converters need the fundamental component, respective phasor and stationary and fundamental instantaneous symmetrical components for their control systems. Several fundamental component estimation methods do not give information about the phasor, so they do not allow the calculation of the instantaneous symmetrical components.

This paper proposes an estimation method for the fundamental phasor and frequency from the fundamental component. It can be applied to any fundamental component estimation or filtering method in order to calculate the instantaneous symmetrical components. The proposed method combined with the adaptive band-pass filter gives a better or equivalent performance as the high performance EPLL and DFT methods.

References

[1] M.S. Sachdev, R. Das, “Understanding Microprocessor-Based Technology Applied to Relaying”, Report of Working Group I16 of the Power Systems Relaying Committee of the IEEE, Feb. 2004.

[2] M.D. Kusljevic, “A Simple Recursive Algorithm for Frequency Estimation”, *IEEE Trans. on Instrumentation and Measurement*, vol. 53, nº 2, pp. 335-340, Apr. 2004.

[3] M. Karimi-Ghartemani and M.R. Iravani, "A Method for Synchronization of Power Electronic Converters in Polluted and Variable-Frequency Environments”, *IEEE Trans. on Power Systems*, vol. 19, no. 3, pp. 1263-1270, Aug. 2004.

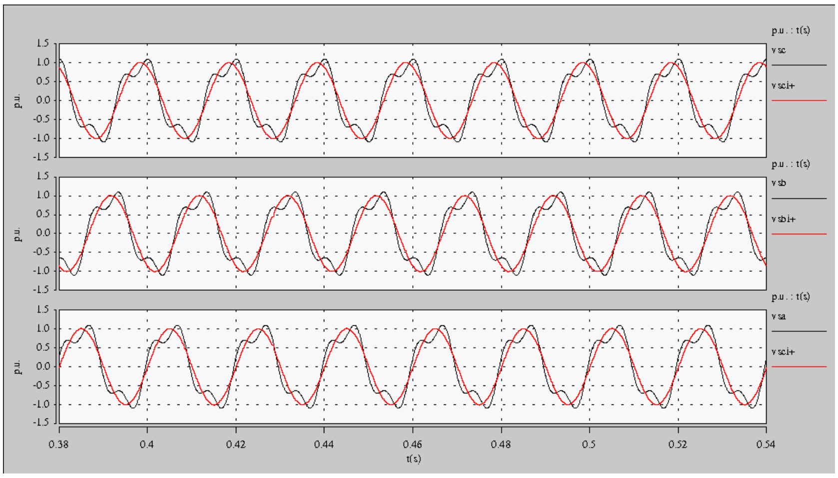

Fig. 12. Immunity test to 3rd harmonic perturbation by adding to the grid voltage homopolar harmonics with 0.3 p.u. for the 3rd harmonic with +50º relative to phase *a*.

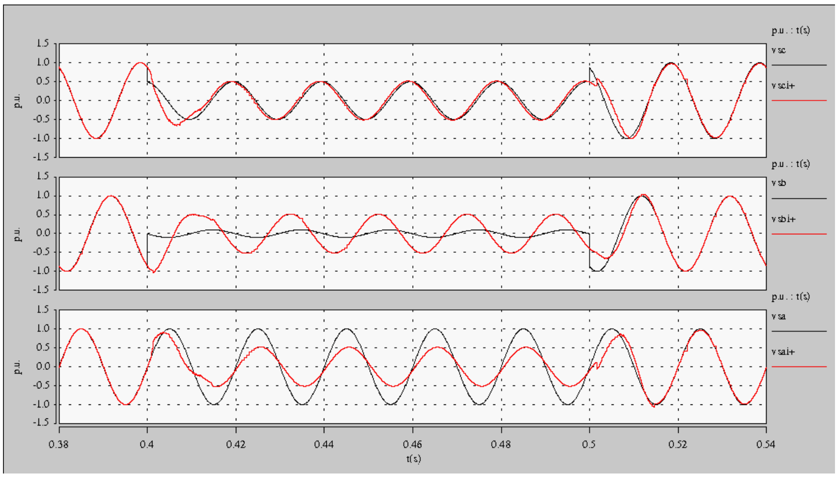

Fig. 13. Asymmetrical voltage sag response of the proposed method (case 1): amplitudes (*abc*) of 1.0, 0.1 and 0.5 and phases (*abc*) of +120º, -175º and 100º.

Table I. Performance comparison of the three methods:
1- single phase; 3- three phase / T- Transient; P- Permanent

Case	Mode	Criteria	EPLL	DFT	Proposed
Sag, 50%	1/T	ST	0.032; 0.028	0.039; 0.033	0.012; 0.012
Swell, 170%	1/T	ST	0.033; 0.030	0.039; 0.033	0.027; 0.013
Phase step, 25º	1/T	ST	0.060; 0.061	0.044; 0.033	0.014; 0.014
Freq. step, +5 Hz	1/T	ST	0.050; 0.049	0.025; 0.038	5.01; 2.75
AC, 30%, 10 Hz	1/P	IAE	0.0059	0.0054	0.0091
Noise, *S/N*=10 dB	1/P	IAE	0.0020	0.0020	0.0005
Start up	3/T	ST	0.080	0.028	0.040
Sag, 50%	3/T	ST	0.029; 0.031	0.020; 0.020	0.016; 0.018
Swell, 170%	3/T	ST	0.036; 0,030	0.020; 0.020	0.026; 0.018
3rd harmonic, 30%	3/P	THD%	30; 0.9	30; 0.9	30; 1,1
AsySag - 1	3/T	ST	0.031; 0.068	0.042; 0.040	0.025; 0.030
AsySag - 2	3/T	ST	0.028; 0.030	0.019; 0.035	0.017; 0.018

[4] M. Wang and Y. Sun, "A Practical, Precise Method for Frequency Tracking and Phasor Estimation", *IEEE Trans. on Power Delivery*, vol. 19, nº 4, pp. 1547-1552, Oct. 2004.

[5] O. Vainio, S. J. Ovaska and M. Pöllä, "Adaptive Filtering Using Multiplicative General Parameters for Zero-Crossing Detection", *IEEE Trans. on Industrial Electronics*, vol. 50, nº 6, pp. 1340-1342, Dec. 2003.

[6] N.A. Losic, "A Quadrature-Based Phase-Locked Loop", in *Proc. of the IECON'2003, 29th Annual Conference of the IEEE Industrial Electronics Society*, pp. 2957-2962, 2003.

[7] H.-L. Jou, H.-Y. Chu, C.-L. Huang and C.-H. Chen, "A Shortest Data Window Algorithm for Detecting the Peak Value of Sinusoidal Signals", *IEEE Trans. on Industrial Electronics*, vol. 31, nº 5, pp. 424-425, Oct. 1990.

[8] M.R. Iravani and M. Karimi-Ghartemani, "Online Estimation of Steady State and Instantaneous Symmetrical Components," *IEE Proc.-Generation Transmission and Distribution*, vol. 150, nº 5, pp. 616-622, Sept. 2003.