A FAST INSTANTANEOUS METHOD FOR SEQUENCE EXTRACTION

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Abstract –**Harmonics and unbalance causes several problems to equipments connected in AC mains. This work proposes a real time method to obtain the positive and negative sequence components and/or harmonics that require nor coordinate transform neither signal filtering. Numerical simulation and experimental results are showed to validate the proposed method.**

Keywords **– active filters, harmonics, power quality, sequence extraction, protection relays**

I. INTRODUCTION

Distorted and unbalanced voltages/currents in electric systems cause several negative effects in power systems [7],[12], [23]-[29],[35],[36].

Real time extraction of unbalances and/or or harmonics is demanded in some applications like active compensators and protective relays. Many strategies were developed for unbalanced components and/or harmonics extraction [1]-[4], [6], [8], [9], [11], [13]-[18], [20], [21], [22], [26], [28], [29], [31], [32],[34] and [35]. Among them, the well known methods are: positive synchronous reference frame (RSP) and negative synchronous reference frame (RSN) [8], [26], the real time detection using space vectors (DTRVE) [32], the instantaneous active and reactive theory (PQ) [2],[30] and the direct injection of negative sequence (DSNI) [9]. A comparative study about some of these strategies is done by [5], [10] and [19].

This paper is based on the work developed by [10],[34]. It proposes an algorithm based on the "symmetrical components theory" that requires nor coordinate transform neither signal filtering. It uses only algebraic calculations. This method allows extracting only the fundamental positive and/or negative sequence and/or harmonics (section 3). Experimental results using Matlab - Simulink software and Analog DSP ADMC401 are presented (section 4).

II. APPLICATIONS OF THE PROPOSED METHOD

The proposed algorithm can extract positive, negative sequence and harmonics components of a corrupt signal and be applied to active power filters, dynamic voltage restorers, power quality analyzers and protective relays systems.

III. PROPOSED METHOD FOR CALCULATING THE INSTANTANEOUS REFERENCE

A. Algorithm description

Eq. (1) calculates the phasors of the symmetrical components ($\dot{S}_0,\dot{S}_+,\dot{S}_-$) of a set of three phase signals (current or voltage) ($\dot{S}_R,\dot{S}_S,\dot{S}_T$) [24] and [33]:

$$\begin{bmatrix}\dot{S}_0\\ \dot{S}_+\\ \dot{S}_-\end{bmatrix}=\underbrace{\frac{1}{3}\cdot\begin{bmatrix}1 & 1 & 1\\ 1 & 1\angle 120^o & 1\angle -120^o\\ 1 & 1\angle -120^o & 1\angle 120^o\end{bmatrix}}_{M}\cdot\begin{bmatrix}\dot{S}_R\\ \dot{S}_S\\ \dot{S}_T\end{bmatrix}=\mathbf{M}\cdot\begin{bmatrix}\dot{S}_R\\ \dot{S}_S\\ \dot{S}_T\end{bmatrix} \quad (1)$$

Zero sequence signals can be extracted using (2). To get the unbalanced signals, in three-phase three wire systems, it is necessary to separate the negative sequence (3).

$$\begin{bmatrix}\dot{S}_0\\ 0\\ 0\end{bmatrix}=\frac{1}{3}\cdot\begin{bmatrix}1 & 1 & 1\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\cdot\begin{bmatrix}\dot{S}_R\\ \dot{S}_S\\ \dot{S}_T\end{bmatrix} \quad (2) \qquad \begin{bmatrix}0\\ 0\\ \dot{S}_-\end{bmatrix}=\frac{1}{3}\cdot\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 1 & 1\angle -120^o & 1\angle 120^o\end{bmatrix}\cdot\begin{bmatrix}\dot{S}_R\\ \dot{S}_S\\ \dot{S}_T\end{bmatrix} \quad (3)$$

To obtain the desired signals in rst frame it is necessary to multiply the signals of (3) by the inverse matrix (M^{-1}) from (1), so obtain (4).

$$\begin{bmatrix}\dot{S}_{ref\_r-}\\ \dot{S}_{ref\_s-}\\ \dot{S}_{ref\_t-}\end{bmatrix}=\mathbf{M}^{-1}\cdot\frac{1}{3}\cdot\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 1 & 1\angle -120^o & 1\angle 120^o\end{bmatrix}\cdot\begin{bmatrix}\dot{S}_R\\ \dot{S}_S\\ \dot{S}_T\end{bmatrix}=-\frac{1}{3}\cdot\begin{bmatrix}-1 & 1\angle 60^o & 1\angle -60^o\\ 1\angle -60^o & -1 & 1\angle 60^o\\ 1\angle 60^o & 1\angle -60^o & -1\end{bmatrix}\cdot\begin{bmatrix}\dot{S}_R\\ \dot{S}_S\\ \dot{S}_T\end{bmatrix} \quad (4)$$

The matrix operation showed in (4) can be divided into two matrixes: the first one contains the real terms and second one the imaginary terms multiplied by –j, according (5).

$$\begin{bmatrix}\dot{S}_{ref\_r-}\\ \dot{S}_{ref\_s-}\\ \dot{S}_{ref\_t-}\end{bmatrix}=\frac{1}{3}\cdot\left[-\begin{bmatrix}-1 & 1/2 & 1/2\\ 1/2 & -1 & 1/2\\ 1/2 & 1/2 & -1\end{bmatrix}-j\cdot\begin{bmatrix}0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\\ -\frac{\sqrt{3}}{2} & 0 & \frac{\sqrt{3}}{2}\\ \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0\end{bmatrix}\right]\cdot\begin{bmatrix}\dot{S}_R\\ \dot{S}_S\\ \dot{S}_T\end{bmatrix} \quad (5)$$

For steady state operation ([10],[34],[37]) the phasor equations (4) and (5) can be rewritten in time domain, resulting in (6) and (7). The phase shift of 60º (-60º) or -90º (90º) can be implemented by time delaying the original signals by a time interval corresponding to the desired angles at the fundamental frequency. The time delaying can be implemented by saving a determined number of samples. The delay of 90º (signals ($s_{r-90}(t)$, $s_{s-90}(t)$, $s_{t-90}(t)$) can be implemented by saving the last N/4 measured samples. The advance of 90º is accomplished by the delayed signals multiplied by –1. The delay of 60º ($s_{r-60}(t)$, $s_{s-60}(t)$, $s_{t-60}(t)$) can be accomplished by saving the last N/6 measured samples. The 60º phase advanced signals ($s_{r60}(t)$, $s_{s60}(t)$, $s_{t60}(t)$) can be obtained by using the last N/3 measured and saved samples, equivalent to a delay of -120º, with opposite signal. , (N is the number of samples per period, at the fundamental frequency).

$$\begin{bmatrix} s_{r-}(t) \\ s_{s-}(t) \\ s_{t-}(t) \end{bmatrix} = -\frac{1}{3}\cdot\left[\begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}\begin{bmatrix} s_r(t) \\ s_s(t) \\ s_t(t) \end{bmatrix} + \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} s_{r60}(t) \\ s_{s60}(t) \\ s_{t60}(t) \end{bmatrix} + \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}\cdot\begin{bmatrix} s_{r-60}(t) \\ s_{s-60}(t) \\ s_{t-60}(t) \end{bmatrix}\right] \quad (6)$$

$$\begin{bmatrix} s_{r-}(t) \\ s_{s-}(t) \\ s_{t-}(t) \end{bmatrix} = \frac{1}{3}\cdot\left[-\begin{bmatrix} -1 & 1/2 & 1/2 \\ 1/2 & -1 & 1/2 \\ 1/2 & 1/2 & -1 \end{bmatrix}\begin{bmatrix} s_r(t) \\ s_s(t) \\ s_t(t) \end{bmatrix} + \begin{bmatrix} 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{\sqrt{3}}{2} & 0 & \frac{\sqrt{3}}{2} \\ \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \end{bmatrix}\cdot\begin{bmatrix} s_{r-90}(t) \\ s_{s-90}(t) \\ s_{t-90}(t) \end{bmatrix}\right] \quad (7)$$

The same reasoning can be applied to calculate the positive sequence, only changing 60º (-60º) to –60º(60º) (8) or -90º (90º) (9).

$$\begin{bmatrix} s_{r+}(t) \\ s_{s+}(t) \\ s_{t+}(t) \end{bmatrix} = -\frac{1}{3}\cdot\left[\begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}\cdot\begin{bmatrix} s_r(t) \\ s_s(t) \\ s_t(t) \end{bmatrix} + \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} s_{r-60}(t) \\ s_{s-60}(t) \\ s_{t-60}(t) \end{bmatrix}\cdot + \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}\cdot\begin{bmatrix} s_{r60}(t) \\ s_{s60}(t) \\ s_{t60}(t) \end{bmatrix}\right] \quad (8)$$

$$\begin{bmatrix} s_{r+}(t) \\ s_{s+}(t) \\ s_{t+}(t) \end{bmatrix} = \frac{1}{3}\cdot\left[-\begin{bmatrix} -1 & 1/2 & 1/2 \\ 1/2 & -1 & 1/2 \\ 1/2 & 1/2 & -1 \end{bmatrix}\begin{bmatrix} s_r(t) \\ s_s(t) \\ s_t(t) \end{bmatrix} - \begin{bmatrix} 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{\sqrt{3}}{2} & 0 & \frac{\sqrt{3}}{2} \\ \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \end{bmatrix}\cdot\begin{bmatrix} s_{r90}(t) \\ s_{s90}(t) \\ s_{t90}(t) \end{bmatrix}\right] \quad (9)$$

The operations defined by eqs. (6),(7),(8),(9) will be called as A, B, C, D respectively. Operations A and B provide the same result for the fundamental frequency. The same occurs for operation C and D. The methods were originally developed for the fundamental frequency. Harmonic components will present different behaviors according to their order and phase sequence for he operations A, B, C, D. Table I and Table II present the gain and phase (º) displacement resulting for the use of the operations A, B, C, D, and the cascaded cases A+B and C+D for odd and even harmonics respectively (positive and negative sequence).

TABLE I – Gain and angle (degrees) for operations A, B, C, D, A+B, C+D for odd harmonics, positive and negative sequences.

operation	A	B	C	D	A+B	C+D
1ºseq+			$1\angle 0$	$1\angle 0$		$1\angle 0$
1ºseq-	$1\angle 0$	$1\angle 0$			$1\angle 0$	
3ºseq+		$1\angle 0$				
3ºseq-				$1\angle 0$		
5ºseq+	$1\angle 0$			$1\angle 0$		
5ºseq-		$1\angle 0$	$1\angle 0$			

TABLE II – Gain and angle (degrees) for operations A, B, C, D, A+B, C+D for even harmonics, positive and negative sequences.

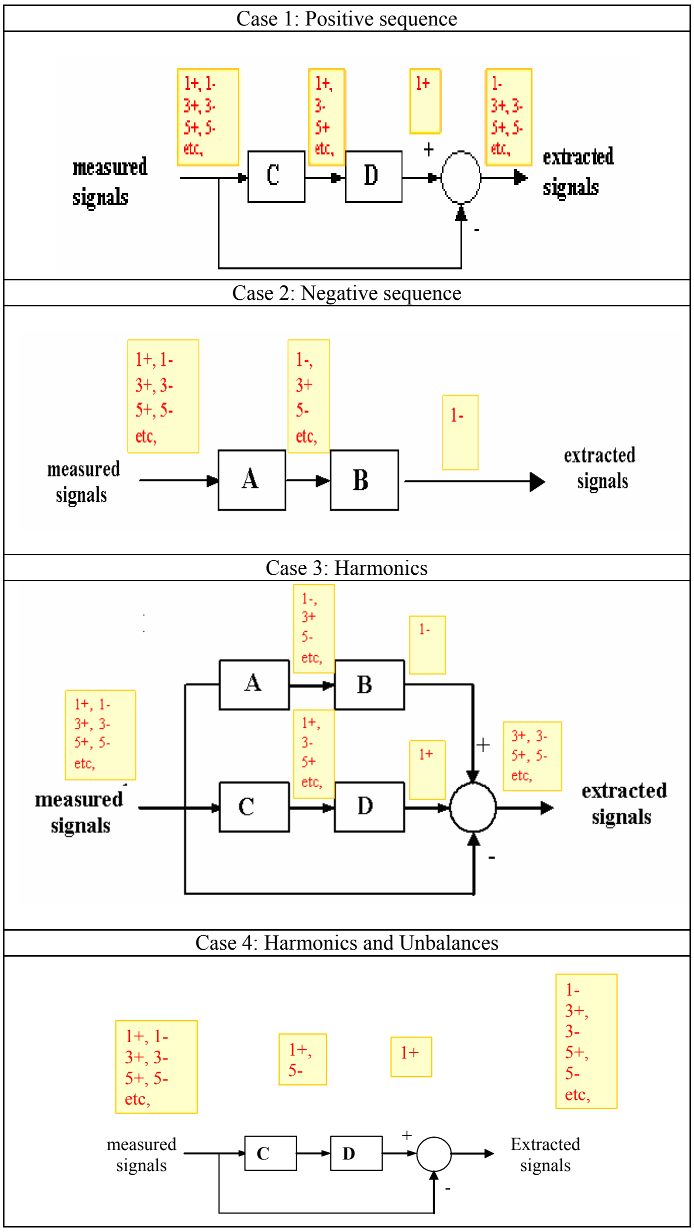
operation	A	B	C	D	A+B	C+D
2ºseq+	$\frac{1}{3}\angle 0$	$\frac{7}{10}\angle 45$	$\frac{2}{3}\angle -60$	$\frac{7}{10}\angle -45$	$\frac{7}{30}\angle 45$	$\frac{14}{30}\angle -105$
2ºseq-	$\frac{2}{3}\angle -60$	$\frac{7}{10}\angle -45$	$\frac{1}{3}\angle 0$	$\frac{7}{10}\angle 45$	$\frac{14}{30}\angle -105$	$\frac{7}{30}\angle 45$
4ºseq+	$\frac{2}{3}\angle 60$	$\frac{7}{10}\angle -45$	$\frac{1}{3}\angle 0$	$\frac{7}{10}\angle 45$	$\frac{14}{30}\angle 15$	$\frac{7}{30}\angle 45$
4ºseq-	$\frac{1}{3}\angle 0$	$\frac{7}{10}\angle 45$	$\frac{2}{3}\angle 60$	$\frac{7}{10}\angle -45$	$\frac{7}{30}\angle 45$	$\frac{14}{30}\angle 15$
6ºseq+	$\frac{2}{3}\angle -60$	$\frac{7}{10}\angle 45$	$\frac{2}{3}\angle 60$	$\frac{7}{10}\angle -45$	$\frac{14}{30}\angle -15$	$\frac{14}{30}\angle 15$
6ºseq-	$\frac{2}{3}\angle 60$	$\frac{7}{10}\angle -45$	$\frac{2}{3}\angle -60$	$\frac{7}{10}\angle 45$	$\frac{14}{30}\angle 15$	$\frac{14}{30}\angle -15$
8ºseq+	$\frac{1}{3}\angle 0$	$\frac{7}{10}\angle -45$	$\frac{2}{3}\angle -60$	$\frac{7}{10}\angle 45$	$\frac{7}{30}\angle -45$	$\frac{14}{30}\angle -15$
8ºseq-	$\frac{2}{3}\angle -60$	$\frac{7}{10}\angle 45$	$\frac{1}{3}\angle 0$	$\frac{7}{10}\angle -45$	$\frac{14}{30}\angle -15$	$\frac{7}{30}\angle -45$
10ºseq+	$\frac{2}{3}\angle 60$	$\frac{7}{10}\angle 45$	$\frac{1}{3}\angle 0$	$\frac{7}{10}\angle -45$	$\frac{14}{30}\angle 105$	$\frac{7}{30}\angle -45$
10ºseq-	$\frac{1}{3}\angle 0$	$\frac{7}{10}\angle -45$	$\frac{2}{3}\angle 60$	$\frac{7}{10}\angle 45$	$\frac{7}{30}\angle -45$	$\frac{14}{30}\angle 105$

For odd harmonics, operations A (C) presents the same gain for (1+6n) order positive sequence (neg. seq) harmonics (n=0,1,2,....) and for (5+6n) order negative sequence (pos.seq.). Operations B and (D) presents the same gain for (3+4n) seq+(-) and (1+4n)seq-(+) harmonics. The cascaded application of operations AB (CD) presents the same gain for (11+12n)seq+(-) and (1+12n)seq-(+) harmonics. For even harmonics, operations A and C presents the same gain for (2+6n), (4+6n) and (6+6n) harmonics. Operations B and D presents the same gain for (2+4n) and (4+4n) harmonics. Cascaded application of operations AB and CD presents the same gain for (2+12n), (4+12n), (6+12n), (8+12n), (10+12n) and (12+12n) harmonics. For all operations, even harmonics are not cancelled but only minimized. For additional attenuation, the operations blocks can be cascaded.

B. Strategies to separate the individual disturbances

A careful analysis of table I show that it is possible to combine operators (A, B, C, D) to obtain different compensation strategies (table III). Only odd harmonics are considered in the four cases. Case 1 shows how the positive sequence of the fundamental component can be extracted from harmonic corrupted, unbalanced signals, by the cascaded application of C and D operations. Similarly, Case 2 shows the extraction of the negative sequence signal by using A and B operations. It is suitable for calculating the reference signal of unbalance compensators. Case 3 extracts all the harmonic components and is suitable for using in harmonic filters. Case 4 extracts the negative sequence and harmonics.

TABLE III – DESIRED EXTRACTION



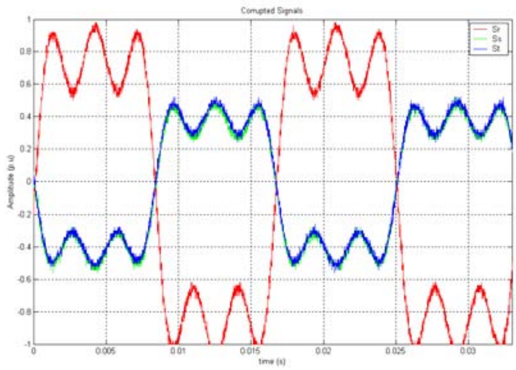


Fig. 1 Test signal

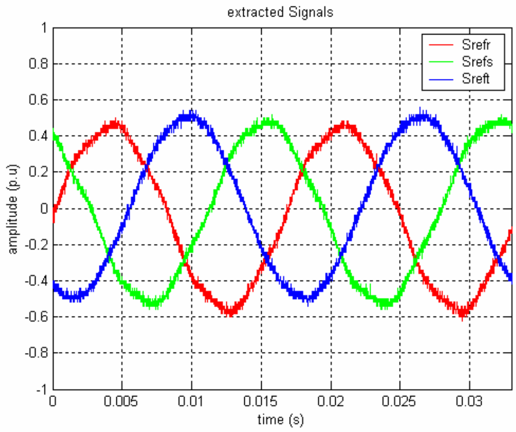


Fig. 2 Negative sequence signal extracted by process AB

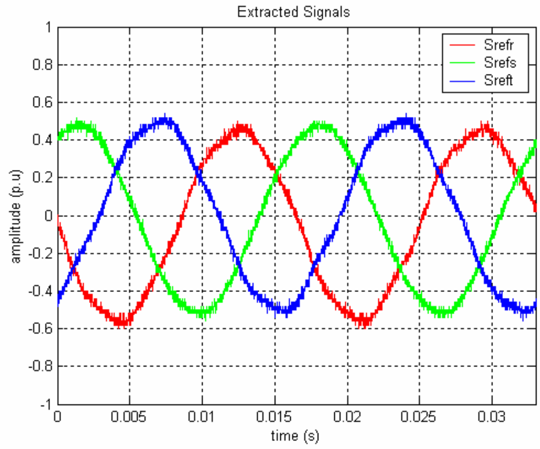


Fig. 3 Positive sequence Signal extracted by process CD

IV. SIMULATION AND EXPERIMENTAL RESULTS

The methods were simulated for each case showed in Table III, using the software MATLAB [37]. Transient response is presented in table IV [37]. Processing time (for ADMC401) is presented in table V. Corrupted test signal is showed in (Fig.1) and steady state extracted signals for methods AB and CD are showed in Figs. (2), (3), (4) and (5).

TABLE IV – TRANSIENT RESPONSE (related to the period of the fundamental signal)

Method	A	B	C	D	AB	CD
Theory	1/3	¼	1/3	¼	3/5	3/5
Simulation	1/3	¼	1/3	¼	3/5	3/5
Experimental	1/3	¼	1/3	¼	3/5	3/5

Table V – Processing Time (for ADMC401)

Method	A	B	C	D	AB	CD
Time (us)	7.6	9	7.6	9	15.4	15.4

The proposed method assumes that the period of the signal is known, to generate the delayed signals (($s_{r\text{-}90}(t)$, $s_{s\text{-}90}(t)$ e $s_{t\text{-}90}(t)$), ($s_{r\text{-}60}(t)$,$s_{s\text{-}60}(t)$,$s_{t\text{-}60}(t)$), ($s_{r60}(t)$,$s_{s60}(t)$,$s_{t60}(t)$)). A PLL can be used to instantaneously track the signal period. If a PLL is not used, and a fixed period equal to the nominal value is used, errors may arise from this method. To verify the possibility of operation without PLL the frequency response for the case 2 (table III) was evaluated for 1, 3, 5, 7 harmonic components of the input signal (fig. 4). The amplitude error of the extracted fundamental negative sequence is quite small (2%) for a large variation (50 to 70 Hz) of the input signal. Phase delay, by the other side, is quite large (180 degrees for

50Hz), making this method not viable for some applications. The delays were based on a 60Hz signal.

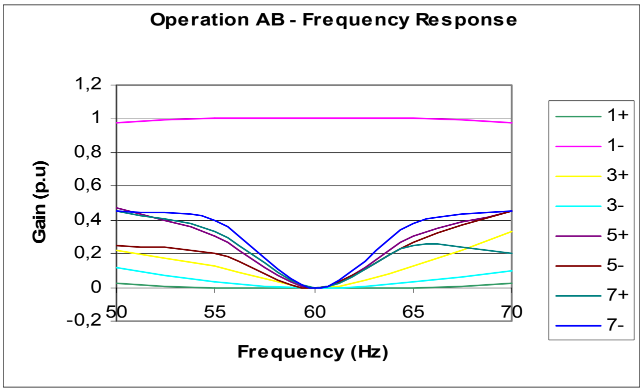
Positive sequence is adequately attenuated (gain= 0,02 for 50Hz).

Harmonic components, which are expected to be fully cancelled by case 2 algorithm, have a poor attenuation for signal frequencies slightly far from 60Hz. Figure 5 presents the frequency response for case 1 (CD operation).

Operation without a PLL is only feasible for signals with small frequency variation, which occurs in equipment connected to strong, interconnected power systems. For weak systems, fed for example by Diesel-Generators, PLL-less operation is possible only for low distorted voltages and currents.

V. CONCLUSIONS

This paper proposes real time algorithms to extract any combination of positive, negative sequence and/or harmonics of a corrupted signal. The processing uses nor coordinate transform neither signal filtering. It can be easily implemented in a DSP, presents a good extraction performance, needs no filtering, has low numerical complexity and presents fast response (less than one fundamental period). It is suitable for many applications like, active power filters, dynamic voltage restorers, power quality analyzers, protective relay, and others. Operation for varying fundamental frequency and the use of PLL to estimate the signal period is discussed.



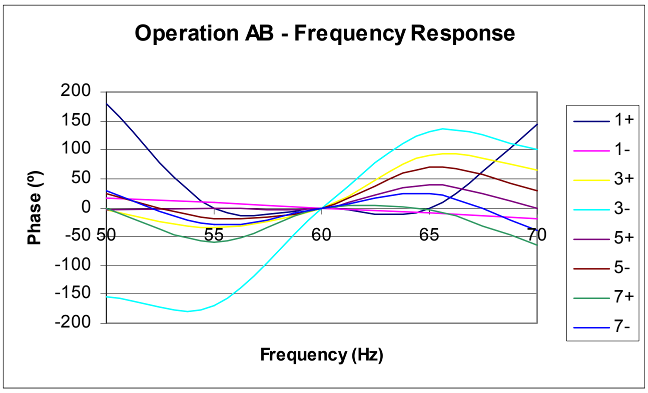
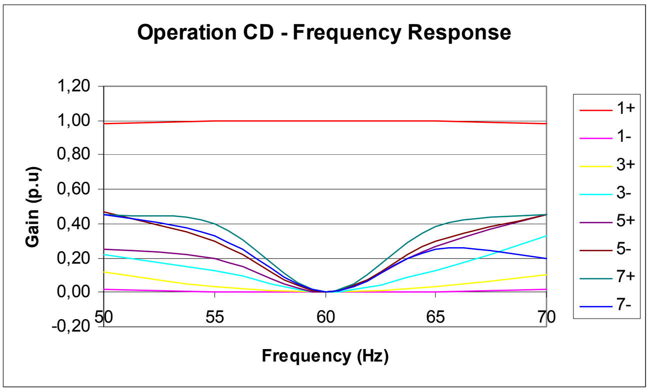


Fig. 4 Operation AB – Frequency Response of Case 2 for various harmonics and phase sequences
Upper: gain Lower:phase



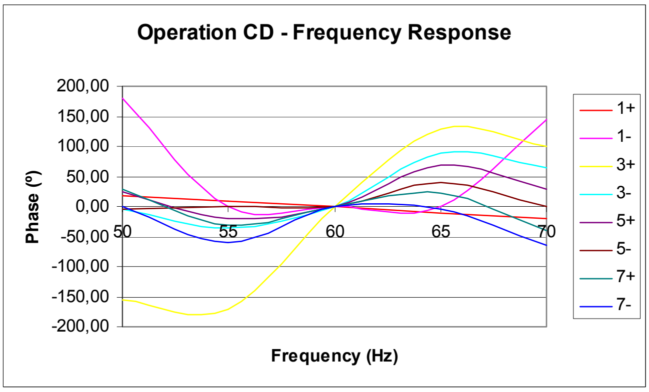


Fig. 5 Operation CD – Frequency Response of Case 1 for various harmonics and phase sequences
Upper: gain Lower: phase

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