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Error analysis of phase detector based on Clarke transform and arctangent function in polluted grids

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ABSTRACT

Extracting phase information from a three-phase disturbed signal is a recurrent topic in power systems. The phase detector based on the Clarke transform and the arctangent function is a widely used technique to this end. However, the nonlinear nature of this method can derive in an error increment in the estimated phase angle when the input signal is distorted. These errors take the form of oscillating and constant terms and are not generally analyzed in the literature. Therefore, this work presents an error analysis of this phase detector that assesses its causes and effects. To do so, the disturbances over the estimated phase are modeled, the reduction of the phase detector performance is described, and the adverse effects produced by the absence of the pre-filter stage are discussed.

1. Introduction

Knowing the instantaneous phase angle of a signal is essential for the normal operation of many devices and applications, such as AC motors control [1–3], distributed generation systems [4–8] and power quality measurement systems [9]. This is because the precision of the method used for grid synchronization can affect systems performance significantly. For example, in power electronics converters related to distributed generation systems applications, a poor synchronization can result in an increased current harmonics injection and/or the injection of reactive power in an uncontrollable manner.

For single phase systems, phase detectors based on a single multiplier and classical Phase-locked Loops (PLLs) are widely used to obtain the instantaneous phase angle of the input signal [10,11]. On the other hand, for three-phase systems, a commonly used method for that task is the Clarke transform, which allows to represents the input signal in the stationary reference frame, and the subsequent calculation of the arctangent function. Among the applications of this phase detector in power systems are: synchronism systems [12–17] and sequence detectors [18–20].

When the three-phase signal is distorted, the estimated phase angle obtained by the Clarke transform and the arctangent function is distorted as well, leading to a poor performance of this phase detector. As a result, a common practice is to add filter stages to mitigate the disturbance effects, which can be implemented either before or after this method is applied. However, the limitations and restrictions of these solutions are not often analyzed.

On the other hand, although there are more efficient synchronization methods in the literature [7,13,17], the phase detector based on the Clarke transform and the arctangent function is a widely used technique due to its simplicity, mainly in industrial applications where a simple and well-known method is preferred over a more complex but efficient one.

As a result of the widespread use of this technique and the lack of a formal analysis of its performance under distorted operational conditions, in this work, the effects of disturbances on the estimated phase angle using the Clarke transform and arctangent function are modeled. The performance degradation of the phase detector is described, and the adverse effects produced by the absence of filtering before the phase detector are discussed. The generation of a DC phase error in the estimated phase angle is investigated, since this error cannot be mitigated by post-filtering stages, and so leads to deteriorated performance. Finally, this work provides an analysis tool to evaluate the convenience of use of the phase detector based

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on the Clarke transform and arctangent function, by means of the computation of the phase error.

This paper is organized as follows. Section 2 reviews the operation principle of Clarke transform. The effect of input distortion in the phase detector based on Clarke transform and arctangent function is characterized in Section 3. In Section 4, some methods proposed in the literature, which use this technique for grid synchronization, are evaluated. Finally, Section 5 sets out the conclusions drawn.

2. Clarke transform

The Clarke transform is widely used in the literature to represent three-phase signals in the stationary reference frame [21]. In this way, the signal is modeled by a space vector whose two components preserve the initial phase, frequency and amplitude information with respect to the original system. As a result of the orthogonal relationship between its components, the instantaneous phase angle can be easily estimated by implementing an arctangent function.

This method assumes that the three-phase signal is composed of three ideal sinusoidal signals with equal initial phase, amplitude and frequency; and a constant phase difference of 120° between them. Under these conditions, this phase detector accurately estimates the instantaneous phase angle of a three-phase system.

However, when the three-phase signal is distorted by imbalances or harmonic components, the space vector components are also distorted, leading to poor performance of the phase detector. Under these operation conditions, the three-phase signal can be modeled in the stationary reference frame as:

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = V_{+1}\begin{bmatrix} \cos(\varphi_u(k)) \\ \sin(\varphi_u(k)) \end{bmatrix} + \sum_{\substack{n=-\infty \\ n\neq 0,1}}^{\infty} V_n \begin{bmatrix} \cos(n\varphi_u(k)+\varphi_n) \\ \sin(n\varphi_u(k)+\varphi_n) \end{bmatrix} \tag{1}$$

where $\varphi_u(k)$ is the system phase angle, V_{+1} is the amplitude of the positive sequence fundamental component, n identifies the nth harmonic, which can either be a positive ($n>1$) or a negative ($n<0$) sequence; and V_n and φ_n are the amplitude and initial phase of the nth harmonic, respectively. Note that the initial phase of the positive sequence fundamental component is equal to zero since it is adopted as the reference of the mathematical model.

Eq. (1) is the classical mathematical model of a stationary reference frame representation of a distorted three-phase signal. To obtain a more compact and convenient expression, $\varphi_u(k)-\varphi_u(k)$ is added to the argument of the second term of Eq. (1), resulting in:

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = V_{+1}\begin{bmatrix} \cos(\varphi_u(k)) \\ \sin(\varphi_u(k)) \end{bmatrix} + \sum_{\substack{n=-\infty \\ n\neq 0,1}}^{\infty} V_n \begin{bmatrix} \cos(n\varphi_u(k)+\varphi_n+\varphi_u(k)-\varphi_u(k)) \\ \sin(n\varphi_u(k)+\varphi_n+\varphi_u(k)-\varphi_u(k) \end{bmatrix} \tag{2}$$

Operating with the second term, this equation can be rewritten as:

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = V_{+1}\begin{bmatrix} \cos(\varphi_u(k)) \\ \sin(\varphi_u(k)) \end{bmatrix} + \sum_{\substack{n=-\infty \\ n\neq 0,1}}^{\infty} V_n \cos((n-1)\varphi_u(k)+\varphi_n) \begin{bmatrix} \cos(\varphi_u(k)) \\ \sin(\varphi_u(k)) \end{bmatrix} + \sum_{\substack{n=-\infty \\ n\neq 0,1}}^{\infty} V_n \sin((n-1)\varphi_u(k)+\varphi_n) \begin{bmatrix} -\sin(\varphi_u(k)) \\ \cos(\varphi_u(k)) \end{bmatrix} \tag{3}$$

and then:

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = V_\gamma \begin{bmatrix} \cos(\varphi_u(k)) \\ \sin(\varphi_u(k)) \end{bmatrix} + V_\delta \begin{bmatrix} -\sin(\varphi_u(k)) \\ \cos(\varphi_u(k)) \end{bmatrix} \tag{4}$$

where

$$\begin{cases} V_\gamma = V_{+1} + \displaystyle\sum_{\substack{n=-\infty \\ n\neq 0,1}}^{\infty} V_n \cos((n-1)\varphi_u(k)+\varphi_n) \\ V_\delta = \displaystyle\sum_{\substack{n=-\infty \\ n\neq 0,1}}^{\infty} V_n \sin((n-1)\varphi_u(k)+\varphi_n) \end{cases} \tag{5}$$

Finally, using the following trigonometric identity:

$$A\sin(x)+B\cos(x)=\sqrt{A^2+B^2}\cos(x-\tan^{-1}[A/B]) \tag{6}$$

and working with Eq. (4), it results in:

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = \sqrt{V_\gamma^2+V_\delta^2}\begin{bmatrix} \cos(\varphi_u(k)+\tan^{-1}[V_\delta/V_\gamma]) \\ \sin(\varphi_u(k)+\tan^{-1}[V_\delta/V_\gamma]) \end{bmatrix} \tag{7}$$

Eq. (7) proves that distortion in three-phase signals affects the amplitude and phase of space vector components. As a result, the extraction of the positive sequence component requires the mitigation of other components in an efficient manner.

3. Effect of distortion in phase detector

This section deals with the adverse effects produced by distortion in the estimated phase angle calculated by the phase detector based on the Clarke transform and the arctangent function.

3.1. Mathematical model of phase error

Assuming a three-phase signal represented in the stationary reference frame, the estimated phase angle (φ_{est}) can be calculated by:

$$\varphi_{est}(k)=\tan^{-1}\left[\frac{v_\beta(k)}{v_\alpha(k)}\right] \tag{8}$$

It is worth noticing that this calculus does not contemplate the fourth quadrant generated by $v_\alpha(k)$ and $v_\beta(k)$. Yet such consideration seems irrelevant for the present analysis. Replacing Eq. (7) in Eq. (8), the estimated phase results in:

$$\varphi_{est}(k)=\tan^{-1}\left[\frac{\sin(\varphi_u(k)+\tan^{-1}[V_\delta/V_\gamma])}{\cos\varphi_u(k)+\tan^{-1}[V_\delta/V_\gamma])}\right] \tag{9}$$

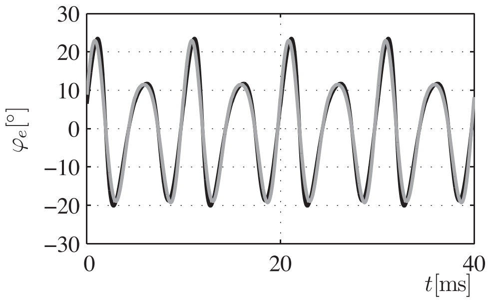

Fig. 1. Phase detector error (black) and theoretical error (gray) for a 30% of a 5th positive sequence harmonic and a 10% of a 7th positive sequence harmonic.

and canceling the arctangent function, the estimated phase angle results in:

$$\varphi_{est}(k) = \varphi_u(k) + tan^{-1}\left[\sum_{\substack{n=-\infty \\ n\neq 0,1}}^{\infty} \frac{V_n}{V_\gamma}\sin((n-1)\varphi_u(k)+\varphi_n)\right] \quad (10)$$

Finally, assuming that $V_{+1} \gg V_n$, Eq. (11) can be approximated as:

$$\varphi_{est}(k) \approx \varphi_u(k) + \sum_{\substack{n=-\infty \\ n\neq 0,1}}^{\infty} \frac{V_n}{V_{+1}}\sin((n-1)\varphi_u(k)+\varphi_n) \quad (11)$$

Eq. (11) shows that distortion in three-phase signal leads to $\varphi_{est}(k) \neq \varphi_u(k)$, due to the generation of oscillating terms related to the original disturbances. For instance, a fifth harmonic component generates a fourth harmonic in the estimated phase, if it is a positive sequence ($n = 5$), or a sixth harmonic if it is a negative sequence ($n = -5$). A similar conclusion is drawn for the phase detector based on the Clarke and Park transforms [21].

Fig. 1 illustrates the comparison between the phase detector error (Eq. (10)) and the theoretical error (Eq. (11)) calculated by subtracting the real phase signal from the estimated phase angle ($\varphi_e = \varphi_{est} - \varphi_u$). The input signal is affected by a 30% of the 5th positive sequence harmonic ($n = 5$) and a 10% of the 7th positive sequence harmonic ($n = 7$). Note that, despite the fact that the fundamental component is not much higher than the harmonic component ($V_{+1} > V_n$), only a minor difference can be observed between the signals shown in the figure. As a consequence, Eq. (11) allows to obtain a good estimation of the phase angle calculated by this detector.

3.2. Distortion in phase error

The differences observed in Fig. 1 are explained by the generation of harmonic terms that Eq. (11) does not predict, since V_γ is not equal to V_{+1}. In this section, these extra terms and their consequences on the phase error are analyzed.

Fig. 2 displays the phase error harmonic distortion (Discrete Fourier Transforms of φ_e) for different operation conditions, where φ_{est} is calculated by a phase detector implementation (Eq. (10)). In addition, a theoretical error (Eq. (11)) is added for comparison purposes.

In Fig. 2a, a 30% of the 5th positive sequence harmonic is added to the fundamental component in the three-phase input signal. This perturbation generates an oscillating term of four times the input frequency, and its respective harmonics, of eight and twelve times in the estimated phase angle. The correspondence between the fourth harmonic and the theoretical component predicted by Eq. (11) is verified. This test is repeated with a different harmonic content. In this case, the fifth harmonic is replaced by a 30% of the 7th positive sequence harmonic. The results of this test are provided in Fig. 2b, where the generation of a harmonics six and twelve times the input frequency can be observed. Also, theoretical error correspondence is verified.

Aside from the phase error distortion described in the last paragraph, the nonlinearity of the phase detector can generate new components resulting from the interaction between other components. This can be noticed in Fig. 2c, where the input signal is distorted with both harmonics described in last paragraph. Apart from the components four, six, eight and eleven times the input frequency, a new component ten times such frequency is observed, which results from the interaction between components four and six times the input frequency.

All oscillating terms generated in the estimated phase angle have a frequency equal to an integer multiple of the input frequency without interharmonic or subharmonic components generation. Therefore, based on the same principle, a particular three-phase distorted signal can generate a DC component in the estimated phase angle. To illustrate this, Fig. 2d shows the phase error when the input signal is affected by a 30% of the 5th negative sequence harmonic and a 30% of the 7th positive sequence harmonic. It is worth underlining that in real grids, the fifth and seven harmonics are mainly negative and positive sequences, respectively [22]. Therefore, this case is not an improbable operation condition (except for the adopted amplitudes, which are chosen to highlight this effect). As Eq. (11) predicts, the fifth and seven harmonics generate a 6th harmonic component in the phase error, which, as a result of the phase detector nonlinearity, generate two additional terms, a DC and 12th harmonic component. In this case, the difference between the phase error and the theoretical error is significant given phase detector nonlinearity. As regards synchronous applications, the DC component error reduces the phase detector performance since this error cannot be mitigated for a filter block subsequent to the implementation of this detector. This error is added to the real input phase and leads to a constant phase error in steady state. To reject this error, a filter stage must be implemented before the phase detector or it must be adopted other phase detector, e.g., the Clarke and Park transforms [21].

3.3. Phase error in presence of 5th and 7th harmonics

As it was mentioned in a previous section, in real grids the fifth and seven harmonics are mainly negative and positive sequences, respectively. In addition, together with third harmonics, they are the ones most responsible for waveform distortion in three-phase voltages. Since both generate a DC component that deteriorates the phase detector performance, it is important to quantify the constant error in the estimated phase related to these harmonics. The phase error in the DC component ($\varphi_e|_{n=0}$) is obtained from Eq. (10) by approximating the arctangent function to its argument, resulting in:

$$\varphi_e|_{n=0} \approx \frac{C_1}{C_2}\sin(B_1 - B_2)\left[1 - \frac{V_1}{\sqrt{V_1^2 - C_2^2}}\right] \quad (12)$$

where

$$C_1 = \sqrt{V_{-5}^2 + V_7^2 - 2V_{-5}V_7\cos(\varphi_7 + \varphi_{-5})} \quad (13)$$

$$B_1 = \tan^{-1}\left[\frac{V_7\sin(\varphi_7 + \varphi_{-5})}{-V_{-5} + V_7\cos(\varphi_7 + \varphi_{-5})}\right] + \pi\varepsilon \quad (14)$$

$$C_2 = \sqrt{V_{-5}^2 + V_7^2 + 2V_{-5}V_7\cos(\varphi_7 + \varphi_{-5})} \quad (15)$$

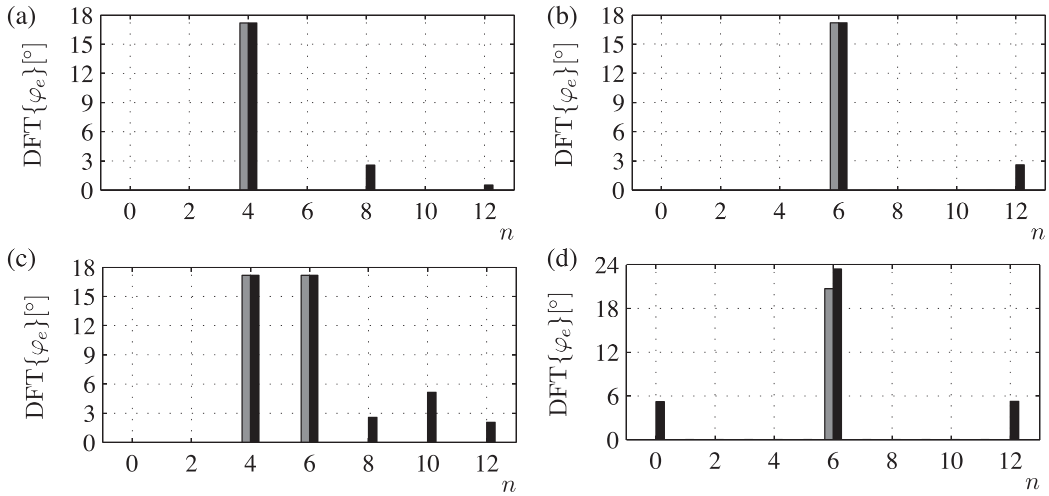

Fig. 2. Phase error harmonic distortion (Discrete Fourier Transforms of φ_e). Error in estimated phase angle (black) and theoretical error (gray). Fundamental component and (a) a 30% of a 5th positive sequence harmonic, (b) a 30% of a 7th positive sequence harmonic, (c) a 30% of a 5th positive sequence harmonic and a 30% of a 7th positive sequence harmonic; and (d) a 30% of a 5th negative sequence harmonic and a 30% of a 7th positive sequence harmonic.

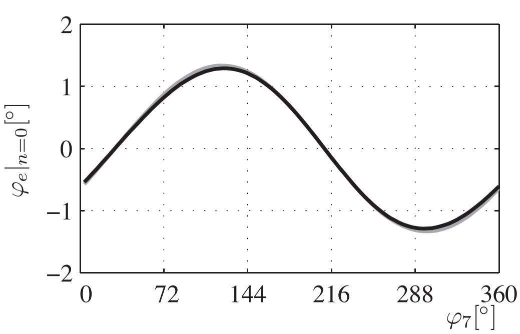

Fig. 3. Phase error in zero frequency ($\varphi_e|_{n=0}$) implementing the phase detector (black) and Eq. (12) (gray).

$$B_2 = \tan^{-1}\left[\frac{V_7\sin(\varphi_7+\varphi_{-5})}{V_{-5}+V_7\cos(\varphi_7+\varphi_{-5})}\right] + \pi\epsilon \tag{16}$$

and

$$\varepsilon = \begin{cases} 1 & \text{if} \quad -V_{-5}+V_7\cos(\varphi_7+\varphi_{-5}) \geq 0 \\ 0 & \text{if} \quad -V_{-5}+V_7\cos(\varphi_7+\varphi_{-5}) < 0 \end{cases} \tag{17}$$

$$\epsilon = \begin{cases} 1 & \text{if} \quad V_{-5}+V_7\cos(\varphi_7+\varphi_{-5}) \geq 0 \\ 0 & \text{if} \quad V_{-5}+V_7\cos(\varphi_7+\varphi_{-5}) < 0 \end{cases} \tag{18}$$

To evaluate this equation, Fig. 3 presents the DC component phase error ($\varphi_e|_{n=0}$) implementing the phase detector and computing Eq. (12). The input signal is distorted with 15% of the fifth and seven harmonics, $\varphi_{-5}=150°$, and φ_7 is adopted as a variable. The figure shows that Eq. (12) provides a good estimation of this constant error.

4. Error in synchronized applications

In order to illustrate the subject matter dealt with herein in an application, some systems related to synchronization are evaluated. Fig. 4 shows the behavior of these systems when 15% of the 5th negative sequence harmonic ($n=-5$) and 15% of the 7th positive sequence harmonic ($n=+7$) are included. Fig. 4 shows the phase error (e_φ) of each method, which are implemented in a floating-point DSP TMS320F28335 (32bits, 150 MHz). The three-phase input signal is obtained by an arbitrary signal generator which also provides the instantaneous phase angle in order to compute e_φ. Channel 1 presents the phase error when the phase detector under study is implemented without a filter stage. As no filtering is used, the phase error presents a high-amplitude oscillation and a poor performance. Channel 2 shows the phase error of the synchronization method described in [13]. In this synchronization methods, the filter stage is performed by the PLL inherent closed-loop action resulting in a post-filter stage. As it can be seen in the figure, the ripple produced by the harmonic components are reduced but, together with this distortion, the synchronization system exhibits a constant phase error which cannot be reduced by modifying the PLL bandwidth. Then, the sequence detector postulated in [18] is evaluated and its phase error is presented in channel 3. This method also involves a post-filter stage implementation, since a Moving Average Filter (MAF) is used to mitigate perturbations after the phase detector. The use of a MAF allows for oscillation mitigation; however, it cannot reduce the constant phase error in steady state. Finally, in channel 4, the synchronization of the fundamental positive sequence estimator presented in [20] is evaluated. This method uses digital notch filters before the arctangent function calculation, which mitigates grid distortions in a more efficient way. As a result, the phase error after the perturbation is zero in

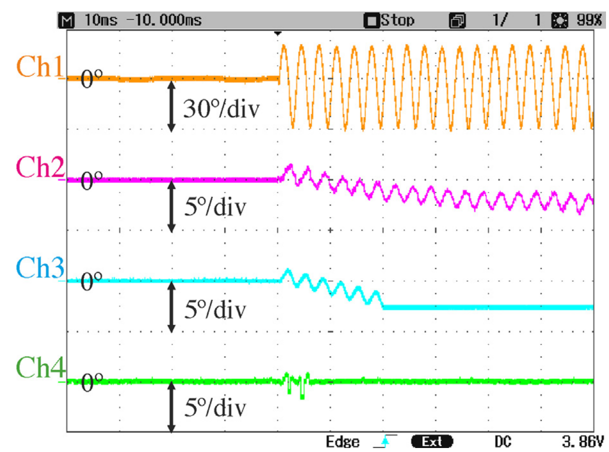

Fig. 4. Evaluation of phase error in several synchronized applications under 15% of the 5th negative sequence harmonic and 15% of the 7th positive sequence harmonic. (Ch1) Phase detector without filter stage,(Ch2) PLL proposed in [13], (Ch3) sequence detector proposed in [18] and (Ch4) fundamental positive sequence estimator proposed in [20].

steady state, proving the advantages of a pre-filter stage instead of a post-filter one.

5. Conclusions

This work presents an error analysis of the phase detector based on the Clarke transform and the arctangent function when the input signal is distorted. The theoretical analysis performed in this work allows to estimate the effects of distortion in the estimated phase angle under no ideal conditions. This mathematical approach of the phase detector performance degradation is suitable for design synchronization methods and to evaluate if they accomplish with requirements of a demanding application.

The analysis performed in this work has demonstrated that, under distorted operation conditions, the estimated phase angle is affected by oscillating terms that deteriorate the performances of this phase detector. Moreover, when the input signal is affected by a 5th and 7th harmonics, which represents a common harmonic content in real grids, a constant error occurs in the estimated phase angle affecting the device synchronization. Unfortunately, this constant error cannot be eliminated with a post-filtering stage. Therefore, the implementation of this phase detector without a pre-filtering stage mitigating the 5th and 7th harmonics from the input signal is not recommended. The analysis performed has allowed to develop an expression to estimate the harmonic content of the phase error as a function of the grid harmonic content. In this way, it is possible to evaluate the convenience of using a phase detector based on the Clarke transform and arctangent function, by means of the computation of the phase error.

On the other hand, it is worthy of mention that this technique remains valid in applications where only frequency synchronization is required.

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