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# Adaptive synchronization of utility in abnormal voltage conditions

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ABSTRACT

Synchronization is a key issue of an inverter-dominated distributed generator to enhance its uninterrupted operation ability in abnormal utility voltage conditions. In this paper, an adaptive-filter-oriented algorithm is proposed to fast and effectively synchronize the positive- and negative-sequence fundamental, even the desired harmonic components of utility voltage. The proposed method consists of two parts. One part is a robust digital phase-locked loop associated with a Sliding-Goertzel-Transform-based filter to track the frequency of utility. The other part is an adaptive module to separate the desired synchronous voltage components from the abnormal utility voltage. Firstly, the mathematical model of the proposed algorithm is established and explained in detail. Then, some useful analysis on the tradeoff between the stability and the convergence of the adaptive module is investigated. Finally, the simulated results by using MATLAB and experimental results performed on a 32-bit fixed-point DSP platform have verified the validation and feasibility of the proposed method, in the cases of distorted and imbalanced utility voltage, frequency step, one-phase or three-phase voltage drops to zero.



## Introduction

Recently, the distribution generation systems (DGSs) and micro-grids integrated with renewable energy sources (RESs) have been paid common attention, due to the emergency demands of smart grid, low emission, and green power [1–5]. To face the hugely increasing penetration of RESs and to reduce the influences of RESs on the utility, the uninterrupted operation abilities of inverter-dominated distributed generators (DGs) in abnormal voltage conditions are focused special concerns [6–8]. Besides, the harmonic voltage ride-through of DGs is becoming a hot topic [9–12]. In general, to achieve the uninterrupted operation of DGs in abnormal utility voltage conditions, how to robustly, fast, and effectively synchronize the desired positive- and negative-sequence fundamental, as well as harmonic voltage components for the controller is a key issue.

Although some literatures have carried out some efforts on the synchronization of DGs in abnormal utility voltage conditions, some of their drawbacks are avoidable and much more attention should be paid. An enhanced phase-locked loop (PLL) based on the decoupling of negative-sequence fundamental component in double synchronous rotating *dq* frame is presented in [13]. In [14], an advanced algorithm is presented to immunize the distorted utility voltage. Moreover, a synchronization approach using variable sampling period filter is introduced in [15] to separate the negative-sequence from the abnormal utility voltage. However, these approaches cannot identify the harmonic voltage components for the synchronization control of harmonic voltage ride-through (HVRT). To synchronize the harmonic voltage of utility, a synchronization approach associated with adaptive notch filter is described in [16]. Nevertheless, the decoupling network will be very complicated if many terms of harmonic are taken into consideration. In [17,18], space vector Fourier transformation and generalized time-delay canceling are employed to fast and accurately detect the desired fundamental and harmonic synchronization components. In [19,20], an advanced algorithm based on multi-complex-coefficient filter is documented to synchronize the positive-, negative-sequence fundamental and harmonic components of utility voltage in abnormal utility condition. To well reject the disturbances from the severely distorted and unbalanced utility voltage, in [21–28], some SOGI-based enhanced PLL algorithms associated with adaptive frequency detectors are well documented. Besides, some other algorithms based on adaptive pre-filter, notch filter, etc. are also introduced in [29–32].

In this paper, an adaptive-filter-oriented algorithm is proposed to synchronize the desired utility voltage components in abnormal

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utility conditions. It can support the uninterrupted operation of DGs in some severe circumstances, like utility failure and distorted utility. The remainder of this paper is organized as follows. In Section 'Mathematical model of the adaptive synchronization algorithm', the mathematical model of the adaptive and recursive algorithm is comprehensively indicated. Besides, the stability and convergence of the algorithm is also investigated analytically. Simulated results on the presented synchronization algorithm are given in Section 'Simulation results'. And, the validations of the proposed algorithm are verified by the experimental results performed on a 32-bit fixed point DSP in Section 'Experimental validations'. Finally, some conclusions are drawn in Section 'Conclusions'.

## Mathematical model of the adaptive synchronization algorithm

According to the method of symmetrical components, the utility voltage $\boldsymbol{u}_{abc} = [u_a, u_b, u_c]^T$ can be decomposed as positive-, negative-, and zero-sequence components [33], which can be expressed as

$$\boldsymbol{u}_{abc} = \sum_p \boldsymbol{u}_{pabc} + \sum_n \boldsymbol{u}_{nabc} + \sum_z \boldsymbol{u}_{nabc} \tag{1}$$

where the positive-, negative-, and zero-sequence voltage, $\boldsymbol{u}_{pabc}$, $\boldsymbol{u}_{nabc}$, and $\boldsymbol{u}_{nabc}$ can be, respectively, written as

$$\boldsymbol{u}_{pabc} = \begin{bmatrix} U_p \sin(p\omega t + \varphi_p) \\ U_p \sin(p\omega t + \varphi_p - 2\pi/3) \\ U_p \sin(p\omega t + \varphi_p + 2\pi/3) \end{bmatrix}$$

$$\boldsymbol{u}_{nabc} = \begin{bmatrix} U_n \sin(n\omega t + \varphi_n) \\ U_n \sin(n\omega t + \varphi_n - 2\pi/3) \\ U_n \sin(n\omega t + \varphi_n + 2\pi/3) \end{bmatrix} \boldsymbol{u}_{zabc} = \begin{bmatrix} U_z \sin(z\omega t + \varphi_z) \\ U_z \sin(z\omega t + \varphi_z) \\ U_z \sin(z\omega t + \varphi_z) \end{bmatrix}$$

where $\omega$ is the fundamental angular frequency of utility; $U_p$ ($U_n$ or $U_z$) and $\varphi_p$ ($\varphi_n$ or $\varphi_z$) represent the amplitude and phase angle of $p$th- ($n$th- or $z$th-) order of positive- (negative- and zero-) sequence components, respectively, while $p \in \{6m+1,\ m \in \boldsymbol{Z}\}$, $n \in \{6m-1,\ m \in \boldsymbol{Z}\}$ and $z \in \{3m, m \in \boldsymbol{Z}\}$. According to the Clarke transformation as expressed as

$$\boldsymbol{T}_{abc/\alpha\beta 0} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{2}$$

whose inverse transformation satisfies $\boldsymbol{T}_{\alpha\beta 0/abc} = \boldsymbol{T}^{-1}_{abc/\alpha\beta 0} = \boldsymbol{T}^{T}_{abc/\alpha\beta 0}$, the utility voltage $\boldsymbol{u}_{abc}$ can be transformed into stationary $\alpha\beta 0$ frame $\boldsymbol{u}_{\alpha\beta 0} = [u_\alpha, u_\beta, u_0]^T$, namely

$$\begin{aligned} \boldsymbol{u}_{\alpha\beta 0} = \boldsymbol{T}_{abc/\alpha\beta 0}\boldsymbol{u}_{abc} &= \frac{\sqrt{6}}{2} \begin{bmatrix} \sum_p U_p \sin(p\omega t + \varphi_p) + \sum_n U_n \sin(n\omega t + \varphi_n) \\ -\sum_p U_p \cos(p\omega t + \varphi_p) - \sum_n U_n \cos(n\omega t + \varphi_n) \\ \sqrt{2}\sum_z U_z \sin(z\omega t + \varphi_z) \end{bmatrix} \\ &= \frac{\sqrt{6}}{2} \begin{bmatrix} U_p \sum_p \left[\sin(p\omega t)\cos\varphi_p + \cos(p\omega t)\sin\varphi_p\right] + U_n \sum_n [\sin(n\omega t)\cos\varphi_n + \cos(n\omega t)\sin\varphi_n] \\ -U_p \sum_p \left[\cos(p\omega t)\cos\varphi_p - \sin(p\omega t)\sin\varphi_p\right] - U_n \sum_n [\cos(n\omega t)\cos\varphi_n - \sin(n\omega t)\sin\varphi_n] \\ \sqrt{2} U_z \sum_z [\sin(z\omega t)\cos\varphi_z + \cos(z\omega t)\sin\varphi_z] \end{bmatrix} \end{aligned} \tag{3}$$

It can be seen from (3) that the positive- and negative-sequence components will not appear in the zero-sequence components $u_0$. Thus, to detect the desired positive- and negative-sequence components for synchronization, the zero-sequence can be ignored in (3). Furthermore, supposing that $p = -n$, Eq. (3) can be rewritten as

$$\begin{aligned} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} &= \frac{\sqrt{6}}{2} \sum_{p=-n} \begin{bmatrix} (U_p \cos\varphi_p - U_n \cos\varphi_n)\sin(p\omega t) + (U_p \sin\varphi_p + U_n \sin\varphi_n)\cos(p\omega t) \\ (U_p \sin\varphi_p - U_n \sin\varphi_n)\sin(p\omega t) - (U_p \cos\varphi_p + U_n \cos\varphi_n)\cos(p\omega t) \end{bmatrix} \\ &= \sum_p \left\{ \begin{bmatrix} \kappa_{p11} & \kappa_{p12} \\ \kappa_{p21} & \kappa_{p22} \end{bmatrix} \begin{bmatrix} \sin(p\omega t) \\ \cos(p\omega t) \end{bmatrix} \right\} \end{aligned} \tag{4}$$

For convenience, in the following parts, the synchronization of positive- and negative-sequence fundamental components ($p = -n = 1$), as well as fifth-order harmonic component ($p = -n = -5$) of utility voltage is taken for example. For the consideration of much more harmonic terms, some similar results can be achieved. According to (4), the estimated utility voltage $\tilde{\boldsymbol{u}} = [\tilde{u}_\alpha, \tilde{u}_\beta]^T$ can be written as

$$\begin{bmatrix} \tilde{u}_\alpha \\ \tilde{u}_\beta \end{bmatrix} = \begin{bmatrix} \kappa_{11} & \kappa_{12} \\ \kappa_{21} & \kappa_{22} \end{bmatrix} \begin{bmatrix} \sin(\omega t) \\ \cos(\omega t) \end{bmatrix} + \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} \sin(5\omega t) \\ \cos(5\omega t) \end{bmatrix} \tag{5}$$

Eq. (5) can be rewritten, in the matrix form, as

$$\tilde{\boldsymbol{u}} = \boldsymbol{K}\boldsymbol{X}_1 + \boldsymbol{H}\boldsymbol{X}_5 \tag{6}$$

where $\tilde{\boldsymbol{u}} = [\tilde{u}_\alpha, \tilde{u}_\beta]^T$ is the objective vector, $\boldsymbol{X}_1 = [\sin(\omega t), \cos(\omega t)]^T$ and $\boldsymbol{X}_5 = [\sin(5\omega t), \cos(5\omega t)]^T$ are the state-variable vectors, coefficient matrixes $\boldsymbol{K}$ and $\boldsymbol{H}$ can be, respectively, expressed as

$$\boldsymbol{K} = \begin{bmatrix} \kappa_{11} & \kappa_{12} \\ \kappa_{21} & \kappa_{22} \end{bmatrix}, \quad \boldsymbol{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

According to (4)–(6), the coefficient matrixes contain the information of fundamental and harmonic components of utility voltage. Therefore, if the coefficient matrixes can be well identified, the desired voltage components for synchronization can be obtained. In the following part, the procedure of the algorithm to estimate the coefficient matrixes will be demonstrated step-by-step according to the adaptive filter theory [34,35]. Taking the mathematical expectation of the error between the actual and the estimated utility voltage, named as $J$, as the minimum objective of the recursive algorithm, it can be derived that