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Stability analysis and concept extension of harmonic decoupling network for the three-phase grid synchronization systems

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ABSTRACT

The harmonic decoupling network (HDN) structure has been widely used as prefilters in grid synchronization techniques, which can accurately extract the fundamental positive- and negative-sequence components and interested harmonics in unbalanced and distorted grid voltages. However, the stability of general HDN is seldom discussed. In this paper, the transfer function expression of general HDN is educed and its stability is proved by the root locus method. Also, it is found that HDN is a multiple-order complex vector filter (MOCVF) in essence. To extend the concept of HDN, the generalized MOCVF (GMOCVF) is proposed. Moreover, an optimized solution to the pole assignment of GMOCVF is presented. As a sequence, GMOCVF can be easily designed to achieve faster dynamic response or better harmonic attenuation compared with HDN under equivalent conditions. In the end, the effectiveness of GMOCVF and the performance comparison between HDN and GMOCVF are verified by the simulation and experimental results.

1. Introduction

Large centralized generators have been the primary method to meet the demand for electricity thus far. However, with the increasing concerns on conventional energy cost, energy security, and relevant environmental issues, distributed generation (DG) become a new focus in power system research [1–4]. Nowadays, more and more renewable energy-based DG units are being connected to the grid with interfacing converters. These power electronic interfacing converters should be controlled carefully to meet the specifications and regulations for interconnected DG under normal operation [5].

Fast and exact synchronization with the voltages at the point of common coupling (PCC) is an essential for the control of grid-connected power converters. However, the increasing numbers of DG units connected to the grid introduce power quality problems and other related issues, which bring challenges to grid synchronization technology. Large-scale introduction of DG units may lead to instability of the voltage profile and harmonic pollution, and imbalances between demand and supply of electricity cause the system frequency to deviate from its rated 50/60 Hz. Furthermore, the restriction of grid code to the distributed generation systems is more rigorous than ever [6,7]. For example, in many countries it requires that the distributed generation systems such as wind turbines should have the ability of fault ride-through to keep controlling the active and reactive power flow during grid faults. Additionally, for the increasing application of nonlinear loads in the distribution system, these harmonic currents drawn from the grid, compounded with higher feeder impedance, could cause considerable voltage distortions at PCC. In some cases, this harmonic content of PCC voltage is needed to be extracted for harmonic compensation methods using DG units themselves [8]. Thus, the grid synchronization technology for distributed generation systems should be designed properly to meet such demands.

The phase-locked loop (PLL) based on the synchronous reference frame (SRF-PLL) is a conventional and likely to be the most widely used synchronization technique for three-phase power system. When the three-phase grid voltage is ideal, SRF-PLL can achieve a fast and precise detection of the grid voltage parameters. However, its performance tends to worsen if grid voltage becomes unbalanced and serious distorted. SRF-PLL may not be an acceptable solution on this occasion.

To improve the performance of SRF-PLL under adverse gird conditions, different advanced synchronization methods have been proposed. Most of these methods employ prefilters or a decoupling network to extract the fundamental positive-sequence component (FPC) from grid voltages and feed it to SRF-PLL. The decoupled double SRF-PLL (DDSRF-PLL) presented in [9] uses a decoupling network to separate the FPC and the fundamental negative-sequence component (FNC) with other harmonics attenuated by low pass filters; another technique with similar functions called Dual Second

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Order Generalized Integrator PLL is presented in [10]. However, Both of the techniques can only extract the FPC and FNC informations, but are incapable of extracting harmonics. In literatures [11–15,23,24], a general harmonic decoupling network (HDN) structure is used to extract all desired frequency components (even harmonics) from input gird voltage signals. However, the stability of general HDN is seldom discussed. There are also other PLL-based synchronization techniques suitable for operating under adverse grid conditions [16–20], such as cascaded DSC PLL (CDSC-PLL) [16], PLL method using the fast Fourier transform (FFT) concept (FFT-PLL) [17], PLL based on adaptive low-Pass notch filter (LPN-PLL) [18], etc, which have been showed in some way with excellent performance.

In this paper, the transfer function expression of general HDN is deduced. Then, the stability of HDN is proved by the root locus method, and how the control parameter ω_c influences its dynamic property is clarified. Based on the analysis of HDN, this paper proposes the generalized multiple-order complex vector filter (GMOCVF). Moreover, an optimized solution to the pole assignment of GMOCVF is presented. As a sequence, GMOCVF can be designed to achieve faster dynamic response or better harmonic attenuation to meet various needs of grid synchronization systems.

This paper is organized as follows. Section 2 presents detailed theoretical derivation and stability proof of HDN. In Section 3, the GMOCVF is proposed and an optimized solution to the pole assignment of GMOCVF is presented. In Sections 4 and 5, the effectiveness of GMOCVF and the performance comparisons between HDN and GMOCVF are verified by simulation and experimental results, respectively. Section 6 provides the conclusions.

2. HDN

2.1. Overview of first order complex-vector filter

The generalized integrators have been widely used in applications processing sinusoidal signals, like frequency detecting, harmonic notch filter, and static error free tracking, etc. Among them, the second order generalized integrator (SOGI) given as $s/(s^2+\omega^2)$ has been studied for scalar sinusoidal signals in many previous works [21–23].

For convenience, the three-phase grid voltages are usually transformed from *abc* to $\alpha\beta$ stationary frame and expressed in terms of space vector as

$$\boldsymbol{v} = \frac{2}{3}\left(v_a + v_b e^{j\frac{2}{3}\pi} + v_c e^{-j\frac{2}{3}\pi}\right) = v_\alpha + j v_\beta \tag{1}$$

where $\boldsymbol{v}$ denotes the three-phase voltage space vector, v_α and v_β are the projections of $\boldsymbol{v}$ on α- and β-axis, respectively.

Consider the case that grid voltages are unbalanced and distorted by harmonics, $\boldsymbol{v}$ can be expressed as the sum of each harmonic:

$$\boldsymbol{v} = \sum_{-m}^{m} \boldsymbol{v}^i \tag{2}$$

where $-m/m$ denotes the low/upper limit of harmonic order, and $\boldsymbol{v}^i$ is given by

$$\boldsymbol{v}^i = \boldsymbol{v}^i_\alpha + j\boldsymbol{v}^i_\beta = V^i\cos(\omega_i t + \varphi_i) + j\sin(\omega_i t + \varphi_i) \tag{3}$$

where $\omega_i = i\cdot\omega_1$ (ω_1 is the fundamental frequency); i can be a positive or negative integer, which represents $\boldsymbol{v}^i$ is in the positive- or negative-sequence.

The SOGI based filters can be used to filter the gird voltages and extract harmonics, but they have no capability to make a distinction between the positive- and negative-sequence at the same frequency. Thus, a positive-/negative-sequence calculation (PNSC) block is needed to do this job.

To distinguish between the positive- and negative-sequence directly, the first order complex generalized integrator (FOGI) can be used to replace SOGI in filters, which is given by

$$R_i(s) = \frac{1}{s - j\omega_i} \tag{4}$$

where ω_i is the central frequency. And it is easy to conclude that

$$\frac{s}{s^2+\omega_i^2} = \frac{1}{2}\left(\frac{1}{s+j\omega_i} + \frac{1}{s-j\omega_i}\right) \tag{5}$$

which means SOGI can be seen as the sum of two FOGIs tuned at the same frequency of positive- and negative-sequence, respectively.

Based on the concept of FOGI, first order complex-vector filter (FOCVF) has been developed, which is introduced by

$$CV_i(s) = \frac{\omega_c R_i(s)}{1+\omega_c R_i(s)} = \frac{\omega_c}{s - j\omega_i + \omega_c} \tag{6}$$

where ω_c is the cutoff frequency and $\omega_c > 0$. And it can be seen that the denominator of transfer function contains a complex coefficient. Thus, the input three-phase voltages must be expressed in form of a complex vector.

To show the filtering characteristic of FOCVF, the bode diagram of $CV_1(s)$ is plotted in Fig. 1. It can be observed that $CV_1(s)$ achieves unity gain and zero phase shift at the center frequency (50 Hz) while attenuates other frequencies. Moreover, $CV_1(s)$ can distinguish between 50 Hz and -50 Hz. It can also be found that a smaller ω_c leads to better harmonic attenuation. However, the dynamic response will become slow at the same time. Therefore, a tradeoff between dynamic response and harmonic attenuation should be considered in the design of FOCVF.

2.2. HDN

To exploit the advantages of FOCVF and to overcome disadvantages, some composite-structure-based prefilters are proposed. Among them, the HDN, also called cross-feedback network, has been developed to be used in the unbalanced and distorted grid voltages condition. It can accurately extract the fundamental component and interested harmonics from the three-phase voltage signals, while making a distinction between the positive and negative sequences.

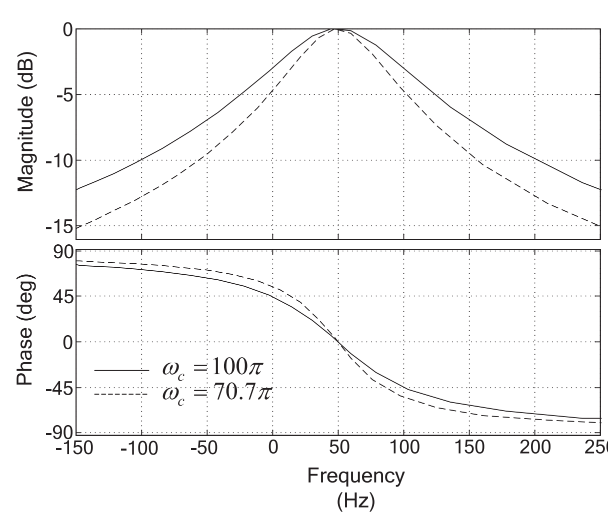

Fig. 1. Bode diagram of FOCVF.