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A novel average filter based phase-locked loop for FACTS devices

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ABSTRACT

The continuous phase-angle of electrical networks is critical information for the auxiliary devices used for improving the stability of the power system. A Phase-Locked Loop (PLL) is the most widely used method for extracting the grid phase accurately to synchronize these devices. In this study, a novel PLL, based on average filter algorithm (APLL), is proposed to extract the amplitude, phase and ±sequences of selected harmonic for the real time applications. It is actualized by integrating the average filters into the simple structure of adaptive notch filter. The accuracy of APLL is demonstrated by giving the mathematical derivation of each property and its validation is evaluated under the distorted system conditions by comparing its results with Fast Fourier Transform at the simulation and experimental case studies.

1. Introduction

The electrical demands of commercial and industrial customers ascend day by day as a result of increasing the utilization of non-linear loads, microprocessor-based industrial controllers, power converters and computer based devices. They naturally produce high-order harmonics and hence, increase the harmonic content of the electrical networks. The Total Harmonic Distortion (THD) can cause Power Quality (PQ) problems such as power losses, voltage sags/swells and negatively affect the safety, quality and economic efficiency of the electricity service. Therefore, the mitigation of PQ problems has especially become a major concern for the industrial customers.

Voltage-source inverter based devices, such as Custom Power Devices (CPD), Flexible AC Transmission Systems (FACTS) and Uninterruptable Power Supplies (UPS), are proposed by the researches for a solution to PQ problems. Advanced-mathematical based control algorithms are used to generate the compensation signals, used for suppression of the harmonic effects. Phase estimation of power system dynamics (voltage and current) is an important data for the control algorithms of these devices. It is generally used to provide the synchronization of equipment such as CPD, FACTS and UPS with the utility grid and to extract their compensation signals for mitigating the negative effects of the disturbances and harmonics.

A Phase-Locked Loop (PLL) is generally used to extract the compensation signals for CPDs and FACTS, to solve the synchronization problems of the generators and UPS with the utility grids. The first description of PLL was implied in 1923 [1] and then, its theoretical derivation was presented to the literature in 1976 [2]. However, PLL could not achieve widespread using until the late 1970's due to the difficulties in its application [3]. Since then, it has made much progress in both its previous versions and widespread using. In the literature, the need for the phase estimation of the power system dynamics was justified by numerous papers. Among of these, Adaptive Notch Filter (ANF) [4–8], Artificial Neural Networks (ANN) [9], Synchronous-Rotating Frame (SRF) [10,11], Three-Phase Arctangent [12], Moving-Average Filter [13] and Sliding Goertzel Transform [14] were generally integrated to PLL algorithms for improving its performance during the unbalanced system conditions.

With the latest developments in the theoretical studies of PLLs, high-order harmonics [15–17] and ±sequences [18–20] are now extracted easier and faster than the Fast Fourier Transform (FFT). Especially, ANF based PLLs have a better capability to extract these variables due to having a simple and flexible algorithm, fast dynamic response, less computation-time and an easy application structure for the microcontrollers [21–24]. In this study, therefore, a new and simple PLL method (APLL) is proposed by integrating the Average Filters (AF) into the simple structure of ANF algorithm. APLL has similar properties with FFT. It precisely extracts the amplitude, phase and ±sequences of the fundamental and high-order harmonics. The error and compensation signals can also be extracted for CPDs and FACTS by using its outputs. Each property of APLL is demonstrated by giving its mathematical derivation and applied to the simple power system. The most important feature of APLL is the reduction of the time-delay, between the input and output signals of classical PLL, almost down to nearly zero by applying proposed flowchart. Its validation is evaluated under the distorted

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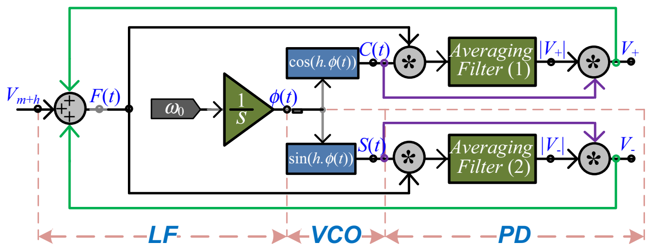

Fig. 1. Basic structure of APLL.

system conditions by performing the simulation and experimental case studies.

The rest of the paper is organized as follows. Section 2 presents the basic properties of APLL with their mathematical equations. In Section 3, the proposed algorithm is explained for the actuators (for an instance micro-processor) by using proposed flowchart. In Section 4, the performance of APLL is observed at the case studies by applying the several voltage disturbances to the test system. Section 5 concludes this paper with the evaluation of the case results. The theory of APLL is demonstrated for the high-order harmonics with the help of mathematical expressions in Appendix A.

2. Basic structure of APLL

A classical PLL has a closed-loop control structure, consisted of Phase Detector (PD), Loop Filter (LF) and Voltage-Controlled Oscillator (VCO) blocks [3]. In the literature, the robustness of PLLs is achieved by integrating of the adaptive methods into their control algorithms. Hence, their performances are improved as well as their control algorithms are complicated when comparing with the classical PLL. Their response-times also increase as a result of this situation.

With this study, it is the first time to integrate the average filters into a structure of ANF for PLL. The number of module is decreased by considering the other PLL algorithms, having the same properties with APLL. Hence, it has a simple algorithm and easy implementation for the actuators. The basic structure of APLL is illustrated in Fig. 1.

Many PLL algorithms include controllers such as Proportional-Integral (PI), Fuzzy and ANN to enhance their robustness against the various disturbances. Additional methods increase the mathematical computations and code lines of the actuators. Also, the coefficients used in the controllers have to be tuned according to the each system conditions. Hence, the computational complexity of the algorithms, in terms of the execution time and the memory required for the computation, is increased for the actuators. By using AF instead of the controllers and adaptive methods, the computational burdens and code lines are reduced and also the situation of parameter tuning is removed. Hence, the simplicity is obtained at its structure and the implementation of its algorithm given in Fig. 2 gets easier than other types of PLL.

Let $V_{m+h}(t)$ represent a grid voltage included the fundamental harmonic ($V_m(t)$) and high-order harmonics ($V_h(t)$). Then, it can be described in the following form.

$$\begin{aligned} V_{m+h}(t) &= V_m(t) + V_h(t) \\ &= V_m \cdot \sin(\omega_0 t + \phi_m) + \sum_{h=2}^{\infty} V_h \cdot \sin(h\omega_0 t + \phi_h) \end{aligned} \tag{1}$$

where 'h' is the harmonic indices, 'ω_0' is the angular velocity, $V_m - \phi_m$ and $V_h - \phi_h$ are the amplitude and phase angle of the fundamental and high-order harmonics, respectively.

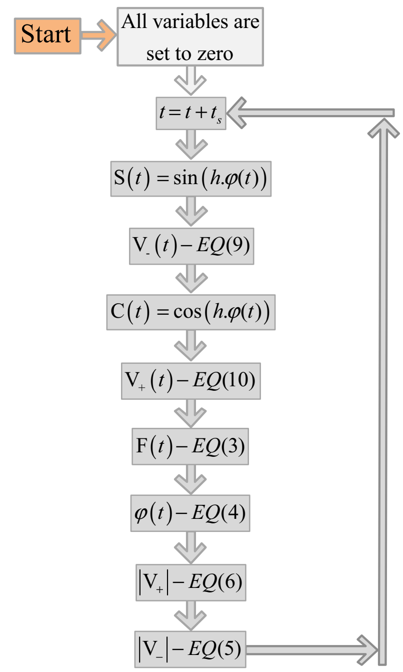

Fig. 2. Proposed flowchart for APLL algorithm.

By entering of $V_{m+h}(t)$ to APLL, the instant estimates of the following features are provided from its outputs.

- $F(t)$, feed-back signal
- $\varphi(t)$, phase of $V_m(t)$
- $V_-(t)$, negative sequences of $V_m(t)$
- $V_+(t)$, positive sequences of $V_m(t)$
- $|V_-|$, amplitude of $V_-(t)$
- $|V_+|$, amplitude of $V_+(t)$
- $S(t)$, per-unit value of $V_-(t)$
- $C(t)$, per-unit value of $V_+(t)$

The dynamics of a three-phase stationary system can be represented by using their positive, negative and zero sequences. If this system is transformed into two-phase stationary system by using Clarke ($\alpha\beta$) Transform, they can be represented by using the positive and negative sequences without considering the zero-sequence [13]. Depending on this assumption, $V_m(t)$ is calculated by using the following equation:

$$V_m(t) = V_+(t) + V_-(t) \tag{2}$$

The algorithm of APLL has a closed-loop structure. Its feed-back signal is obtained from the sequences of the input signal and then used in AFs. It is calculated as follows.

$$F(t) = V_{m+h}(t) + V_+(t) + V_-(t) \tag{3}$$

In the power applications, harmonics of a periodic signal (voltage or current) are extracted by using FFT. Before the calculation process, it only needs the frequency of the fundamental harmonic (f_0) due to taking the samples from the input signal at each-period and then starts to the extract the harmonics. APLL, also, needs the frequency to calculate $\varphi(t)$. Same as FFT, f_0 is used in its algorithm during the extraction of the fundamental and high-order harmonics.