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A three phase PLL with a dynamic feed forward frequency estimator for synchronization of grid connected converters under wide frequency variations

B. Indu Rani, C.K. Aravind, G. Saravana Ilango *, C. Nagamani

Power Converters Research Laboratory, Department of Electrical and Electronics Engineering, National Institute of Technology, Tiruchirappalli, India

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ABSTRACT

This paper presents a synchronization technique to accurately track the phase and frequency of the input signal under large frequency deviations. The hybrid FPLL structure consists of a conventional SRF PLL feedback loop along with a feed forward frequency estimator loop. The advantage of this technique is that the feedback controller has to reduce only the phase error and the frequency error is eliminated by the feed forward controller. This increases the dynamic response of the system under frequency deviations. The performance of the hybrid structure is compared with the conventional SRF PLL and the former shows improved performance over the SRF PLL in terms of filtering characteristics and transient response for wide range of frequency deviations. The steady state error analysis is carried out and the necessary condition for stability is also derived. Simulations are carried out in MATLAB/Simulink and implemented in real time using an ALTERA cyclone II FPGA board. The results obtained for various grid conditions such as unbalance, harmonics, phase jump and frequency deviation demonstrate the phase-tracking ability of the technique.

1. Introduction

The growing demand for clean, reliable and renewable energy is driving society towards distributed generation systems. The increasing penetration of distributed generation system into the grid requires cheap and integrated control systems [1,2]. In grid connected systems, accurate phase angle and frequency of utility voltage is essential since the voltage or current reference is synchronized with the phase of the utility voltage for various applications such as power factor correction, active/reactive power control [3–5]. Many synchronization techniques have been presented over the recent years. In synchronous reference frame (SRF) based Phase Locked Loop (PLL) based systems, the phase angle estimation is adaptively updated by a closed loop mechanism whose objective is to track the actual frequency and phase angle. The simplicity of the structure makes this technique the widely accepted synchronization algorithm for grid connected systems [6]. However, its performance deteriorates under distorted conditions. In such cases, the bandwidth is reduced drastically to improve the filtering characteristics [7] which in turn affect the transient response. Moreover under wide frequency deviations, it introduces a steady state error in the phase angle estimation. The main challenge in the design of PLL employed in grid connected systems is to achieve good dynamic response and zero steady state error under distorted supply and frequency deviations.

Several techniques [8–10] have been proposed to improve the tradeoff between transient response and filtering such as placement of extra filter inside the loop, pre-filter before the phase detector and implementation of complex structures. The use of extra filters in the SRF PLL, such as notch and moving average [8,9] eliminates the ripple due to phase unbalancing and harmonics. The software based PLL employed in series connected converters utilizes delayed cancellation technique [10] to extract the positive sequence component from stationary frame to remove the effect of distortions in supply. However, these systems [8–10] are designed to operate at the nominal frequency and needs modification to work satisfactorily under wide frequency variations.

Several methods [11–14] have been introduced for frequency estimation under distorted conditions. An improved PLL structure proposed for controlling the grid connected equipments consists of multiple filters [11] in series to overcome the limitations of SRF PLL under distorted conditions. Each distortion component is attenuated through dedicated pre-filters and a second order low pass filter is used to remove the distortions in the frequency measurement. The decoupled double synchronous reference frame PLL [12] with two synchronously rotating frames having exactly opposite angular velocities is introduced to handle the unbalanced conditions. This technique is capable of tracking the frequency variations but requires some improvement under harmonic conditions. A robust PLL developed for FACTS devices [13] regulates the system gain in an adaptive control manner. The structure consists of three control

* Corresponding author.
E-mail addresses: indu_b04@yahoo.com (B. Indu Rani), aravindck@gmail.com (C.K. Aravind), gsilango@nitt.edu (G. Saravana Ilango), cnmani@nitt.edu (C. Nagamani).

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units for frequency, phase angle, and voltage magnitude estimation and the improved response under frequency deviations is attributed to the structure that enables independent control of frequency and phase tracking. The three control units are connected together and all the parameters are tuned accordingly. The adaptive linear optimal filter (ALOF) [14] proposes a synchronization algorithm that recursively updates the frequency and the phase angle of the fundamental component of input signal. The learning rate parameter has a significant effect on the frequency characteristics of the system and is a compromise between the accuracy and the convergence speed. The structure includes separate sub filters for eliminating individual harmonics and the harmonic components considered for cancellation depends on the application and the available computational resources. Therefore, the computational load of ALOF depends on the number of harmonics considered for elimination. A novel technique (EPLL) [15] proposed for frequency measurements in power system applications introduce a major modification in the PD section of the PLL structure. This method generates a steady state error of 15 mHz under distorted supply and frequency deviations. Based on [15], a synchronization algorithm that adaptively follows the phase and frequency variations with no steady state error is proposed [16] for three phase applications. This structure utilizes four similar EPLL units for three phase system which complicates the structure and it is difficult to be practically implemented [14]. Dynamic analysis of three single phase PLL algorithms namely the power PLL, park PLL and EPLL utilized in UPS applications is made and useful comparative results are presented [17]. In all the three structures the implementation of the filter and VCO section remain the same with difference in their PD mechanism. The structure of power PLL is similar to that of the conventional PLL and it is based on the principle that the mean fictitious power is zero when the voltage and the fictitious current are in quadrature. The park PLL tracks the deviations in frequency and has two low pass filters in the PD section to remove the ripples. However, in this technique the harmonic rejection capability is increased at the cost of transient response [17]. The EPLL has the highest dynamic response among the three structures but its output signal highly oscillates at second order harmonic frequencies during transient conditions [17].

These approaches [16] attempt to estimate the frequency by increasing the complexity in PD section or concentrates on harmonic elimination [13,14] and updates the filter parameters with respect to frequency. However, most of these methods [14–17], utilize the feedback control technique to track the phase angle and frequency of the signal and the loop filter provides a correction around the nominal frequency. These systems exhibit poor performance for large variation in frequency unless a compromise is made for the filtering characteristics under distorted conditions.

In this paper, a hybrid structure (FPLL) which includes the conventional SRF PLL feedback loop and a feed forward frequency estimator loop are used to track accurately the phase and frequency of the input signal for wide frequency deviations. The hybrid structure is simple to implement and the phase and the frequency estimation is accurate and insensitive to unbalance and harmonic conditions under wide frequency deviations. The interesting feature of proposed system is that the same technique can be extended to any existing PLL techniques employing constant feed forward frequency.

2. The conventional SRF PLL

The three phase voltages V_a, V_b, V_c are represented as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_m \cos\theta \\ V_m \cos(\theta - 2\pi/3) \\ V_m \cos(\theta + 2\pi/3) \end{bmatrix} \tag{1}$$

These signals are transformed into the stationary reference frame signals V_α and V_β using Clarke transformation

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = 2/3 \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2}$$

These signals are transformed to the rotating reference frame using the Park transformation to dq frame.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\theta^* & -\sin\theta^* \\ \sin\theta^* & \cos\theta^* \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = U \begin{bmatrix} \cos(\Delta\theta) \\ \sin(\Delta\theta) \end{bmatrix} \tag{3}$$

$$\text{where} \quad \Delta\theta = \theta^* - \theta \tag{4}$$

and U is the magnitude. The objective is to compute an accurate estimate (θ^*) of the actual phase (θ) of the input signal. Since the phase of a periodic signal is the time integral of its frequency, the angle (θ^*) is obtained by integrating a frequency command (ω^*). The $\Delta\theta$ is set to zero by a PI controller and the PLL gets locked to the utility voltage. Thus the PLL can be treated as a linear control system with the utility magnitude appearing as a gain in the forward path, the plant being a simple integrator. The basic configuration of the SRF based PLL system is shown in Fig. 1. The plant transfer function H(s) can be expressed as

$$H(s) = 1/s \tag{5}$$

The transfer function of the PI controller is

$$G_c(s) = (K_p + K_I/s) \tag{6}$$

where K_p and K_I are the gains associated with PI controller. The PI controller parameters are chosen in accordance with the symmetrical optimum method [7]. According to this method, the magnitude and the phase plot are symmetrical about the cross over frequency ω_c which is at the geometric mean of two corner frequencies of the open loop transfer function. The PI controller can be tuned to have a high bandwidth under balanced conditions. However, to improve the filtering characteristics under distorted conditions, the bandwidth is reduced which slows down the dynamic response.

The open loop transfer function of the system is given by

$$G(s) = \frac{(K_p + K_I/s)}{s} \tag{7}$$

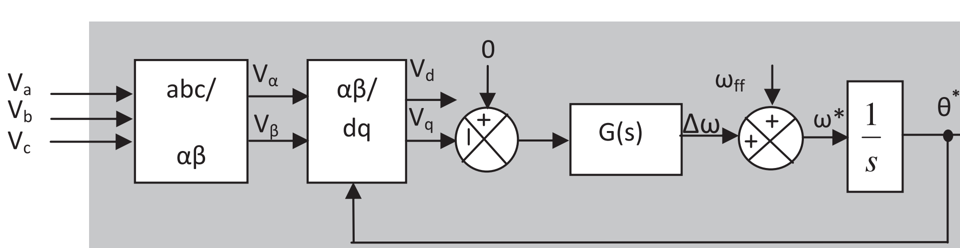

Fig. 1. SRF PLL.