Operation of a Phase Locked Loop System Under Distorted Utility Conditions

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***Abstract*— Operation of a phase locked loop (PLL) system under distorted utility conditons is presented. A control model of the PLL system is developed and recommendations are made on tuning of this model specially for operation under common utility distortions as line notching, voltage unbalance/loss, frequency variations. The PLL is completely implemented in software without any filters. All analytical results are experimentally verified.**

***Index Terms*—Phase locked loop (PLL), utility interface, utility angle, utility synchronization.**

I. Introduction

The phase angle of the utility voltage is a critical piece of information for the operation of most apparatuses as: controlled ac ↔ dc converters, static VAR compensators, cycloconverters, active harmonic filters and other energy storage systems coupled with the electric utility [2]. This information may be used to synchronize the turning on/off of power devices, calculate and control the flow of active/reactive power or transform the feedback variables to a reference frame suitable for control purposes. The angle information is typically extracted using some form of a phase locked loop (PLL) [1]. Besides utility interface applications, PLL methods are also used in motor control to estimate the electrical angular speed of the rotor [3], [4]. The quality of the lock directly effects the performance of the control loops in above applications.

Line notching, voltage unbalance, line dips, phase loss, and frequency variations are common conditions faced by equipment interfacing with electric utility. Any PLL used under such conditions should not only be able to phase lock to utility voltages as quickly as possible and maintain lock but also provide low distortion output.

This paper examines a simple, fast and robust three-phase PLL for utility applications with emphasis on operation under distorted utility conditions. Ample information is available in literature about PLL's as applied to communication systems. It is our intent to treat the PLL system purely as a control problem. The topology used is similar in nature to a field-oriented controller, commonly used for converter/inverter control. A control model of the PLL is developed and used for time- and frequency-domain analyses. Recommendations are made for selection of appropriate regulator gains. The PLL system is completely implemented in software on a DSP. All analytical results are experimentally verified.

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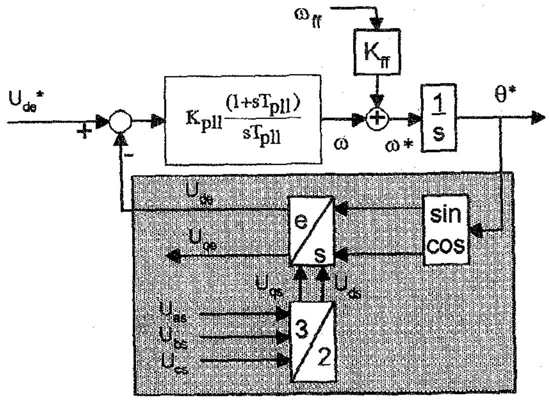

Fig. 1. Control diagram of the phase locked loop.

II. The PLL System

A. Principle of Operation

The basic configuration of the PLL system is shown in Fig. 1. The phase voltages U_{as}, U_{bs}, U_{cs} are obtained from sampled line to line voltages. These stationary reference frame voltages are then transformed to voltages U_{de}, U_{qe} (in a frame of reference synchronized to the utility frequency) using the 3/2 and e/s transformations. The angle θ^* used in these transformations is obtained by integrating a frequency command ω^*. If the frequency command ω^* is identical to the utility frequency, the voltages U_{de} and U_{qe} appear as dc values depending on the angle θ^*.

In the given method, a PI regulator is used to obtain that value of θ^* (or ω^*) which drives the feedback voltage U_{de} to a commanded value U_{de}^*. In other words, the regulator results in a rotating frame of reference with respect to which the transformed voltage U_{de} has the desired dc value U_{de}^*. The frequency of rotation of this reference frame is identical to the frequency of the utility voltage. The Magnitude of the controlled quantity U_{de} determines the phase difference between the utility voltages and $\sin(\theta^*)$ or $\cos(\theta^*)$.

The method results not only in the utility frequency ω^* but also allows one to lock at an arbitrary phase angle θ^* with respect to the utility angle θ. The angle $\Delta\theta$ (Fig. 2) is controlled by the commanded values U_{de}^*. Analytical development of a simplified model suitable for time/frequency domain analysis follows.

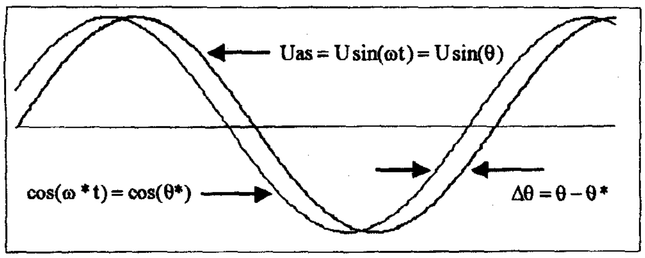

Fig. 2. Input phase voltage and PLL output.

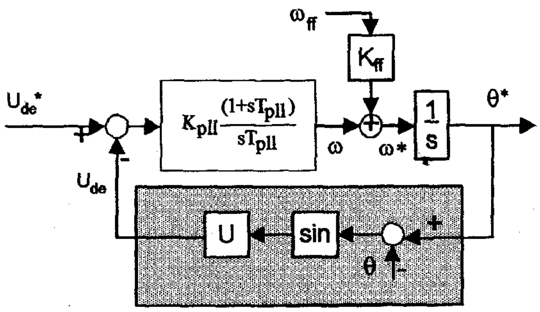

Fig. 3. Simplified control model of the PLL system.

B. Simplified PLL Model

The sampled phase voltages U_{as}, U_{bs}, U_{cs} when transformed to the synchronous frame of reference result in the quadrature voltages U_{ds}, U_{qe} (Fig. 1). In vector control scheme, typically two independent regulators are used to control these voltages. In the PLL presented here, only a single control loop is closed around U_{de}. Assuming a balanced three phase utility, a simplified control model of the PLL can be developed using the following transformations:

$$\begin{bmatrix} U_{as} \\ U_{bs} \\ U_{cs} \end{bmatrix} = \begin{bmatrix} U\cos(\theta) \\ U\cos(\theta - 2\pi/3) \\ U\cos(\theta - 4\pi/3) \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} U_{qs} \\ U_{ds} \end{bmatrix} = \begin{bmatrix} U_{as} \\ (U_{cs} - U_{bs})/\sqrt{3} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} U_{qe} \\ U_{de} \end{bmatrix} = \begin{bmatrix} \cos(\theta^*) & -\sin(\theta^*) \\ \sin(\theta^*) & \cos(\theta^*) \end{bmatrix} \begin{bmatrix} U_{qs} \\ U_{ds} \end{bmatrix}. \tag{3}$$

Substituting (1) and (2) in (3), the voltages U_{qe}, U_{de} are given by (4):

$$\begin{bmatrix} U_{qe} \\ U_{de} \end{bmatrix} = U \begin{bmatrix} \cos(\theta^* - \theta) \\ \sin(\theta^* - \theta) \end{bmatrix} = \begin{bmatrix} \cos(\Delta\theta) \\ \sin(\Delta\theta) \end{bmatrix}. \tag{4}$$

If the error $\Delta\theta$ between the utility angle θ and the PLL output θ^* is set to zero, $U_{qe} = U$ and $U_{de} = 0$. This offers immediate possibility to lock onto the utility voltage by regulation of U_{de} to zero. No information is needed about the magnitude U of the utility voltage.

The simplified control model is shown is Fig. 3. For small values of $\Delta\theta$, the term $\sin(\Delta\theta)$ behaves linearly, i.e., $\sin(\Delta\theta) \sim \Delta\theta$. The PLL can thus be treated as a linear control system with the utility magnitude U appearing as a gain in the forward path, the plant being a simple integrator.

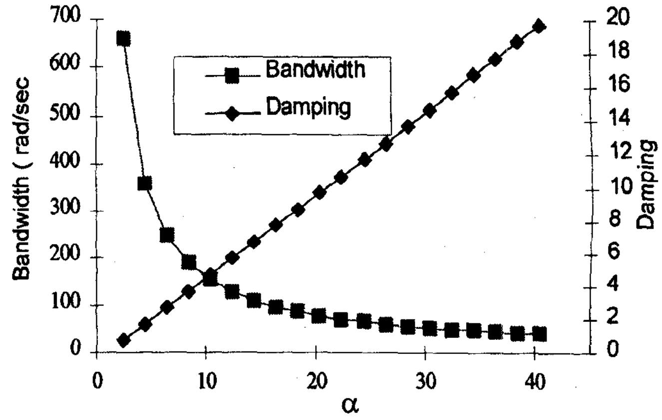

Fig. 4. Control of bandwidth and damping using α.

C. Selection of Gains

With the above configuration, the control problem reduces to picking the correct gains for the model of Fig. 3 for various operating conditions. Taking the sampling delay into account, the plant is a simple lag along with an integrating element (5):

$$H_{\text{plant}} = \left(\frac{1}{1 + sT_s}\right)\left(\frac{U}{s}\right) \tag{5}$$

where T_s is the sampling time. The open-loop transfer function H_{ol} with the controller then becomes

$$H_{\text{ol}} = \left(K_{\text{pll}}\frac{1 + sT_{\text{pll}}}{sT_{\text{pll}}}\right)\left(\frac{1}{1 + sT_s}\right)\left(\frac{U}{s}\right) \tag{6}$$

where K_{pll}, T_{pll} are the gains associated with the PI regulator. This is a standard control problem very similar to a current controlled speed loop of a drive system where the integral term in the plant mimics the mechanical inertia and the lag element emulates the current control loop. Several methods can be used to select the gains based on the desired performance criteria.

The method of *symmetrical optimum* [5] was used to calculate the regulator gains. According to this method, the regulator gains K_{pll} and T_{pll} are selected such that the amplitude and the phase plot of H_{ol} are symmetrical about the crossover frequency ω_c, which is at the geometric mean of the two corner frequencies of H_{ol}. Given a normalizing factor α, the frequency ω_c, K_{pll}, T_{pll} are related as following:

$$\left.\begin{aligned} \omega_c &= 1/(\alpha T_s) \\ T_{\text{pll}} &= \alpha^2 T_s \\ K_{\text{pll}} &= (1/\alpha)(1/(UT_s)). \end{aligned}\right\} \tag{7}$$

Substituting (7) into (6) it can be shown [6] that the factor a and the damping factor ξ are related by the relationship:

$$\xi = \frac{\alpha - 1}{2}. \tag{8}$$

The relationship between α, damping factor ξ and bandwidth ω_c is shown in Fig. 4 for a sampling time $T_s = 100$ μs. By changing α, the system bandwidth and damping can be controlled.