LOOP STABILITY ANALYSIS IN FREQUENCY AND PHASE AUTOMATIC CONTROL SYSTEMS

Baymatova N.T
Tashkent State Technical University, Tashkent, Republic of Uzbekistan email: baymatovanargiz77@gmail.com
Shirinboyev Kamoliddin Jurabek ugli
Student of group 83-24 (RQT) email: shkamoliddin0121@gmail.com

Abstract: *This paper analyzes the stability characteristics of regulation loops in frequency and phase automatic control (FPAC/PLL) systems. The structures of first- and second-order PLL loops, along with their phase shifts and dynamic properties, are comparatively examined. It is shown that, due to the absence of a low-pass filter, first-order loops exhibit limited phase stability and increased sensitivity to noise. In contrast, the inclusion of a low-pass filter in the feedback path of second-order loops enables effective suppression of phase fluctuations, imparts inertial "flywheel" properties to the system, and ensures stable synchronization. In addition, the influence of the loop filter on the capture range and capture time is discussed. The obtained results are of practical importance for the selection and optimization of PLL loop configurations in the design of high-precision synchronization systems.*

Keywords: *frequency and phase automatic control, PLL (phase-locked loop), phase locking, regulation loop, stability, phase shift, low-pass filter, voltage-controlled oscillator (VCO), phase fluctuations.*

At the output of the phase detector, an error signal is generated that is determined by the phase difference between the input signal and the reference signal [1]. A voltage-controlled oscillator (VCO) varies its output frequency according to the control voltage applied to its input [2, 5]. At first glance, it may seem sufficient to form a closed-loop control system by enclosing the system with a feedback path having a certain gain. This approach is similar to classical control schemes based on operational amplifiers. However, a fundamental difference exists in this case. In conventional control systems, the quantity regulated via feedback generally coincides with, or is at least proportional to, the quantity measured to generate the error signal. For example, in amplifiers, the output voltage is measured and, based on this value, the input voltage is adjusted accordingly [4].

In frequency and phase automatic control systems, i.e., phase-locked loop (PLL) systems, a fundamentally different process takes place. In this case, the phase error is measured, while the control action is applied to the oscillator frequency. Since phase is the time integral of frequency, a natural 90° phase shift arises in the control loop [1, 3]. If an additional integrating element is introduced into the feedback path, it produces an extra 90° phase delay. As a result, the total phase shift approaches 180°, and at frequencies where the overall loop gain equals unity, the system may exhibit self-sustained oscillations, indicating a potential loss of stability [1, 4].

One of the simplest ways to address this problem is to remove from the circuit all elements that introduce phase delay, especially at frequencies where the loop gain approaches unity. Practical experience shows that operational amplifiers, although introducing an approximately 90° phase delay over almost the entire operating frequency range, are nevertheless capable of maintaining stable operation. This approach represents the most basic method for resolving phase stability issues and results in the formation of a first-order PLL loop [1, 2]. Structurally, this loop is similar to the general PLL block diagram; however, it differs in that the low-pass filter (LPF) is omitted from the loop [1]. Such a simplified loop exhibits reduced phase delay and can provide stable synchronization over a narrow frequency range; however, it suffers from significant limitations in terms of noise suppression and dynamic performance. Although first-order PLL systems are employed in many practical applications, they do not possess sufficient “flywheel” (inertial) characteristics. As a result, noise and frequency fluctuations present in the input signal are not effectively smoothed and directly affect the output signal. Moreover, in this configuration, the output of the phase detector directly controls the VCO, which prevents maintaining a constant phase relationship between the VCO output signal and the reference signal. In other words, although the system may ensure frequency alignment, stable phase locking at a fixed value cannot be guaranteed. These limitations necessitate the use of higher-order PLL loops in synchronization systems that require high accuracy. To ensure stable operation, an additional low-pass filter is introduced into the feedback path of a second-order PLL loop. This filter provides smoothing properties to the system, resulting in effective suppression of phase fluctuations and noise. At the same time, the inclusion of the filter leads to a reduction in the capture range and an increase in the capture time. In practice, second-order PLL loops are widely used in many applications, since most technical systems require small phase fluctuations of the output signal as well as the presence of a certain degree of “memory” or “flywheel” (inertial) behavior. Second-order loops can exhibit a high loop gain in the low-frequency region, which, when considered by analogy with feedback amplifiers, acts as an important factor in enhancing the phase and amplitude stability of the system [4, 6].

Conclusion. In this paper, the stability characteristics of regulation loops in PLL systems were theoretically analyzed. Although first-order loops are distinguished by their structural simplicity, their noise suppression capability and phase stability were found to be limited. In second-order loops, the introduction of a low-pass filter into the feedback path provides the system with inertial properties and enables effective reduction of phase fluctuations. At the same time, such loops exhibit a reduced capture range and an increased capture time. The performed analysis demonstrates that the use of second-order PLL loops is appropriate for practical systems requiring high accuracy and stable phase synchronization.

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