Texas Instruments

Compensation and Characterization of the TLS223x Phase-Locked Loop

Application Report

July 1996 *Hard Disk Drive Business Unit*

TEXAS INSTRUMENTS

Printed in U.S.A.
0796

SQHA001

TEXAS INSTRUMENTS

Compensation and Characterization of the TLS223x Phase-Locked Loop

July 1996

Hard Disk Drive Business Unit

TEXAS INSTRUMENTS

Printed in U.S.A.
0796

Application Report

Compensation and Characterization of the TLS223x Phase-Locked Loop

John K. Rote
Hard Disk Drive Business Unit

SQHA001

Texas Instruments

IMPORTANT NOTICE

Texas Instruments (TI) reserves the right to make changes to its products or to discontinue any semiconductor product or service without notice, and advises its customers to obtain the latest version of relevant information to verify, before placing orders, that the information being relied on is current.

TI warrants performance of its semiconductor products and related software to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are utilized to the extent TI deems necessary to support this warranty. Specific testing of all parameters of each device is not necessarily performed, except those mandated by government requirements.

Certain applications using semiconductor products may involve potential risks of death, personal injury, or severe property or environmental damage ("Critical Applications").

TI SEMICONDUCTOR PRODUCTS ARE NOT DESIGNED, INTENDED, AUTHORIZED, OR WARRANTED TO BE SUITABLE FOR USE IN LIFE-SUPPORT APPLICATIONS, DEVICES OR SYSTEMS OR OTHER CRITICAL APPLICATIONS.

Inclusion of TI products in such applications is understood to be fully at the risk of the customer. Use of TI products in such applications requires the written approval of an appropriate TI officer. Questions concerning potential risk applications should be directed to TI through a local SC sales office.

In order to minimize risks associated with the customer's applications, adequate design and operating safeguards should be provided by the customer to minimize inherent or procedural hazards.

TI assumes no liability for applications assistance, customer product design, software performance, or infringement of patents or services described herein. Nor does TI warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right of TI covering or relating to any combination, machine, or process in which such semiconductor products or services might be or are used.

Contents

List of Illustrations

Abstract

This application report describes the TLS223x servo-combination predriver, its state machine, phase comparator, and voltage-controlled oscillator (VCO). The TLS223x uses a phase-locked loop (PLL) to commutate a spindle motor. This report describes the selection of the compensation values to ensure proper operation of the PLL and provides an example of this selection process.

Introduction

The TLS223x is a family of servo-combination predrivers used in hard-disk-drive applications. When combined with the TPIC150X power driver, the TLS223x provides the capability to drive an actuator (voice-coil motor) and a spindle (three-phase brushless dc motor). The TLS223x contains the circuitry to commutate the spindle motor. A PLL generates a clocked signal that advances the commutation-state machine through the six electrical states of the spindle.

Circuit Description

The TLS223x uses a PLL to match the commutation frequency to the motor. The phase comparator generates an error, which is the difference in phase between the motor's back-EMF (BEMF) and the output of the VCO. The VCO advances the commutation state. Proportional plus integral (PI) compensation is applied to this phase-error signal. The specific values of the PI compensation determine the PLL operating parameters, such as bandwidth and phase margin. The output of the compensation network drives the VCO. The gain of the VCO is determined by an external capacitor.

Figure 1 shows a model of the TLS223x PLL. This Matlab model is generated from a systems simulation package by The MathWorks, Inc.

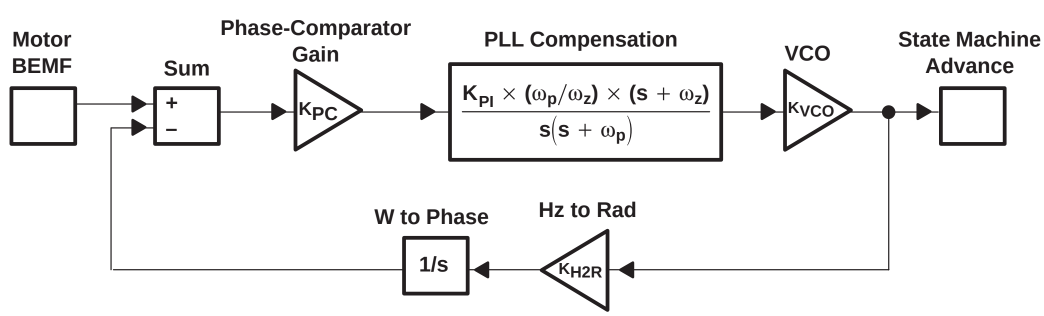


Figure 1. Matlab Model for TLS223x PLL

Commutation Control

The TLS223x connects to the brushless dc motor through the TPIC150X FET bridge (see Figure 2). The state machine controls the commutation switching of the appropriate high- and low-side drivers (HSD and LSD).

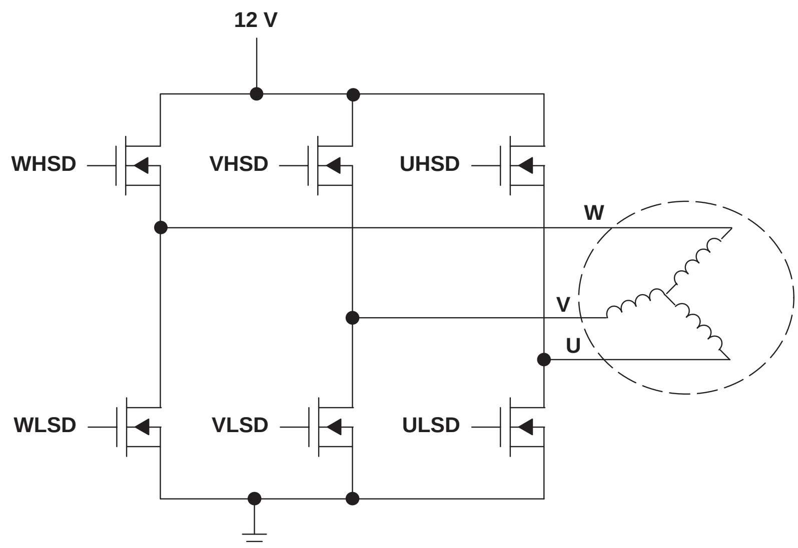


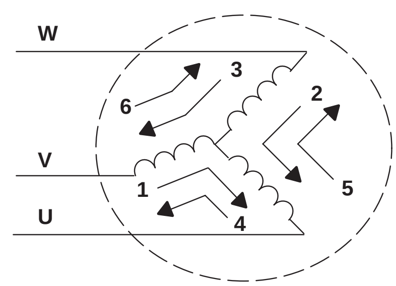
Figure 2. Power Driver FET Bridge

Figure 3 shows the commutation sequence. The current flows through the windings of the motor in the direction of the indicated arrow. The state table (Figure 3a) for state 1 shows the V high-side driver active and the U low-side driver active. The current follows path 1 (Figure 3b) and flows from the V phase of the motor to the U phase.

This flow of current generates a torque, which causes the motor to spin. As the motor spins, a voltage is generated across the windings. This voltage, which is referred to as the BEMF voltage, is observed during each commutation state at the undriven phase.

State	High-Side Active	Low-Side Active
1	V	U
2	W	U
3	W	V
4	U	V
5	U	W
6	V	W

a) State Table of Motor



b) Current Flow in Motor

Figure 3. Commutation Sequence

Phase Comparator

Figure 4 shows the phase comparator. The BEMF voltage is compared to the artificial center-tap voltage to determine whether the switched-current comparator sources or sinks current into the filter network.

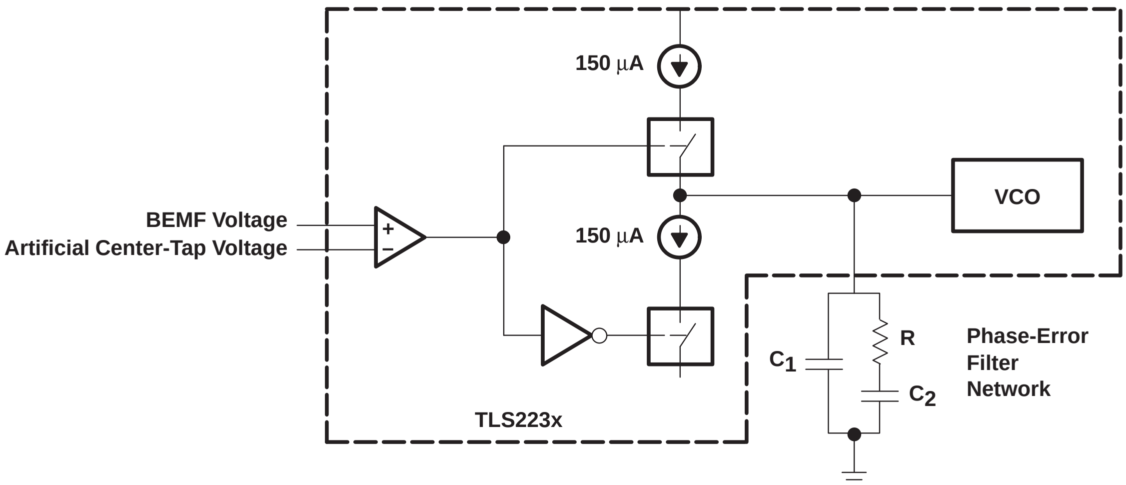


Figure 4. Phase Comparator

The TLS223x generates the BEMF waveform and the artificial center-tap voltage used by the switched-current phase comparator. The artificial center-tap voltage (generated from 12 V/2) is the average of the two driven phases. The BEMF waveform is the undriven phase inverted during every other commutation state (see Figures 5 and 6). Figure 5 shows the BEMF voltage for all three phases. The undriven phase during each commutation interval is indicated at the bottom of the BEMF waveform graph.

The commutation sequence of Figure 3 determines the undriven phase of the motor. The V and U phases are active in state 1, thus, W is the undriven phase (shown on Figure 5 as interval 1 W). The highlighted waveform is the undriven phase for each of the six commutation states of the motor.

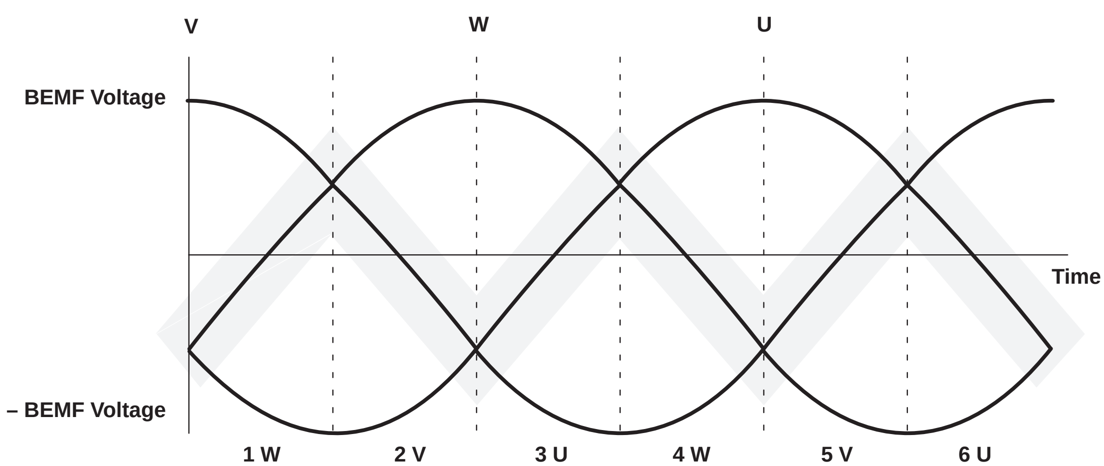


Figure 5. BEMF Waveforms

Figure 6 shows the waveform created when the undriven phase is selected during each commutation interval and the signal is inverted during every other state.

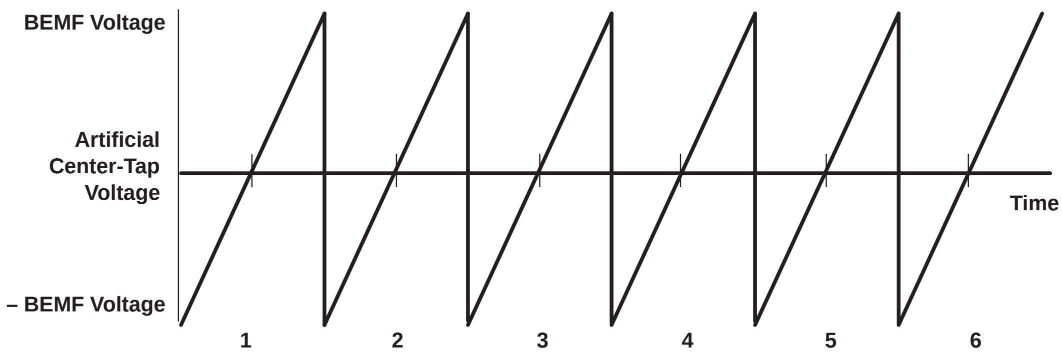


Figure 6. Phase Comparator Waveform

The BEMF voltage is symmetrical around the artificial center-tap voltage when the commutation is matched to the motor (see Figure 6). Under this condition, the phase comparator sources and sinks current with a 50-percent duty cycle. The voltage on the filter network remains relatively constant and the VCO continues to oscillate at the same frequency. If the commutation to the motor slips, the BEMF waveform shifts up or down relative to the artificial center-tap voltage.

Figure 7 shows the case of late commutation. The phase comparator sources longer than it sinks current. The voltage across the filter network increases, causing the VCO to oscillate faster. The commutation catches up with the motor, and the BEMF waveform shifts down until it centers around the artificial center-tap voltage.

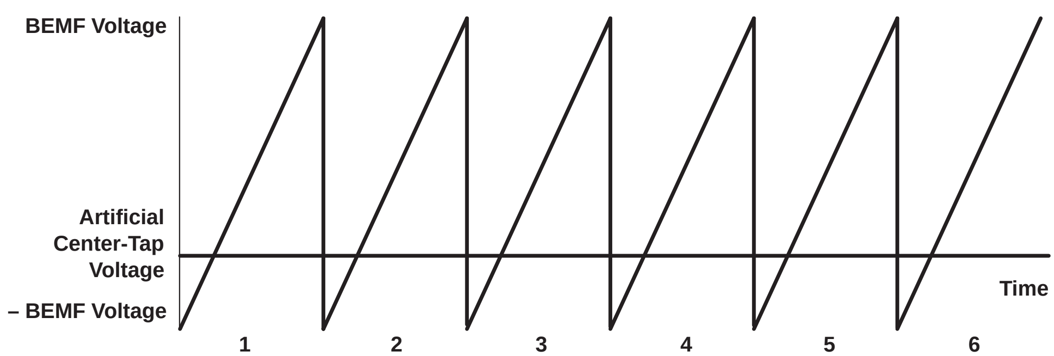


Figure 7. Phase Comparator Waveform for Late Commutation

VCO

Figure 8 shows the VCO. With the lower current source disabled, the voltage across the external capacitor C_{VCO} rises until it reaches the threshold $V_{REF} \times 3/2$ and the lower current source becomes active. The voltage across C_{VCO} then falls until it reaches the threshold of $V_{REF}/2$ and the lower current source turns off. The voltage across C_{VCO} is shown in Figure 9a.

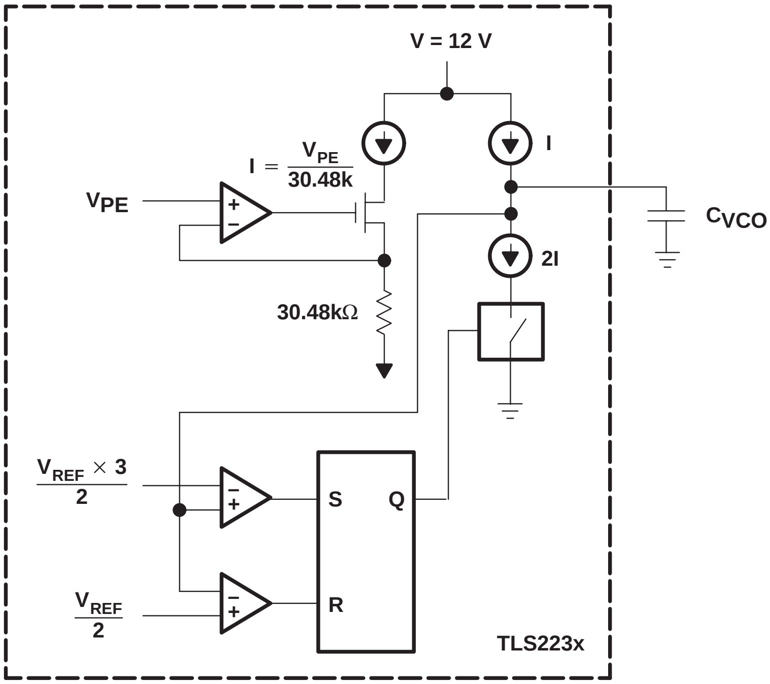


Figure 8. VCO

The voltage at the input V_{PE} controls the rate of oscillation. The magnitude of the current source is:

$$I = \frac{V_{PE}}{30.48k}\ A \tag{1}$$

The charge/discharge of the capacitor is:

$$I = C\frac{dv}{dt} \tag{2}$$

Since the charge and discharge intervals are the same, the oscillation period is equivalent to twice the amount of time required for the voltage to rise from $V_{REF}/2$ to $V_{REF} \times 3/2$ ($\Delta = V_{REF}$):

$$T_O = 2C_{VCO}\frac{V_{REF}}{I} \tag{3}$$

The frequency of oscillation is $1/T_O$. Using equations 1 and 3, the frequency of the VCO is:

$$F_{VCO} = \frac{V_{PE}}{2C_{VCO}V_{REF}30.48k} \tag{4}$$

Figure 9b shows the relationship between the VCO and the signal available on the TLS2231 SENSE/VCO/TACH output pin. This output waveform varies depending on which TLS223x device is used. The commutation state machine shown in Figure 3 advances on every falling edge of this signal.

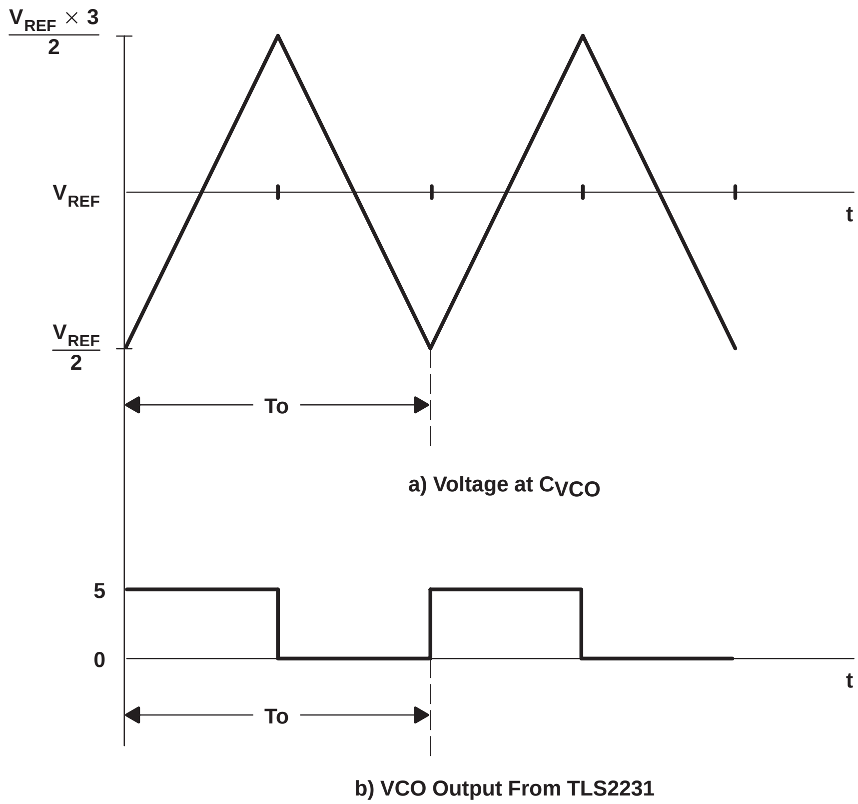


Figure 9. VCO Waveforms

Selecting Compensation Values for the PLL

The Matlab model in Figure 1 is used to select the PLL compensation values. The phase-comparator gain (K_{PC}) is 150 µA per π radians. The value of K_{H2R} (converts frequency from hertz to radians) is 2π. The external components of the TLS223x determine the values for the PLL compensation and gain of the VCO. The remainder of this section details a method for selecting these values.

The gain of the VCO is set so the motor is operating at the desired frequency and the voltage at the filter network is ≈2 V. This ensures that the VCO, which saturates at ≈2.8 V, operates in its linear region and is able to correct errors in phase. The gain is set by the selection of the capacitor connected to the C_{VCO} pin of the TLS223x. When V_{PE} = 2 V, equation 5 solves for C_{VCO}:

$$C_{VCO} = \frac{1}{(F_{VCO} \times 30.48k \times V_{REF})} \tag{5}$$

The value of F_{VCO} is a function of the number of poles and the operating speed of the motor. The frequency is:

$$F_{VCO} = \left(\frac{\#\ \text{poles}}{2}\right)(\text{desired motor rpm})\left(\frac{1\ \text{min}}{60\ \text{s}}\right) \times \left(\frac{6\ \text{commutation states}}{1\ \text{electrical revolution}}\right) \tag{6}$$

The VCO gain for the model in Figure 1 is:

$$K_{VCO} = \left(\frac{F_{VCO}}{V_{PE}}\right) \tag{7}$$

Where:

$$V_{PE} = F_{VCO} \times C_{VCO} \times 30.48k \times 2 \times V_{REF} \text{ (from equation 4)} \quad (8)$$

For example, an 8-pole motor operating at 5400 rpm requires that F_{VCO} = 2160 Hz. Equation 5 provides a nominal value for C_{VCO} = 7590 pF. A commercially available capacitor with a value of 8200 pF is chosen. The phase-error voltage is no longer 2 V, but V_{PE} is 2.16 V. Using equation 7 to solve for K_{VCO}, the value of K_{VCO} is 1000.

With the loop parameters defined, the compensation is selected. The PLL performs well in a bandwidth range of 40–100 Hz. In the example, the compensation achieves a bandwidth of approximately 80 Hz with a phase margin of at least 40 degrees. The phase comparator (see Figure 4) provides the PI compensation. The transfer function is:

$$\frac{K_{PI} \times \left(\frac{\omega_p}{\omega_z}\right) \times (s + \omega_z)}{s(s + \omega_p)} \quad (9)$$

Where:

$$K_{PI} = \frac{1}{(C_1 + C_2)} \quad (10)$$

$$\omega_z = \frac{1}{RC_2} \text{ rad/s} \quad (11)$$

$$\omega_p = \frac{(C_1 + C_2)}{(RC_1C_2)} \text{ rad/s} \quad (12)$$

The desired frequency response is attained if ω_z is chosen to be approximately 1/3 of the bandwidth, ω_c. The chosen value of ω_p is approximately three times the value of ω_c. The bandwidth is set by the filter's gain, K_{PI}. The gain is chosen so that the magnitude (in dB) of the open-loop transfer function is 0 at ω_c.

$$20\log(150e^{-6} \times K_{VCO} \times 2) - 20\log(\omega_c) - 20\log(\omega_z) + 20\log\left(\frac{1}{(C_1 + C_2)}\right) = 0 \quad (13)$$

Solving this for the quantity $C_1 + C_2$:

$$C_1 + C_2 = \frac{1}{\{\log^{-1}[\log(\omega_z) + \log(\omega_c) - \log(150e^{-6} \times K_{VCO} \times 2)]\}} \quad (14)$$

In the example under consideration, $C_1 + C_2$ is $3.55e^{-6}$ μF. Using a capacitor ratio of 10:1 gives C_2 = 3.3 μF and C_1 = 0.33 μF. A resistor is chosen to obtain the desired ω_z.

$$R = \frac{1}{\omega_z C_2} \quad (15)$$

For ω_z = 160 rad/s (i.e., 80 Hz × 2π/3), R is 1.8 KΩ. With this value, ω_p is 1850 rad/s (295 Hz).

Checking the Results

The results are verified by creating the Matlab model shown in Figure 1. The open-loop and closed-loop frequency responses for this model are shown in Figures 10 and 11.

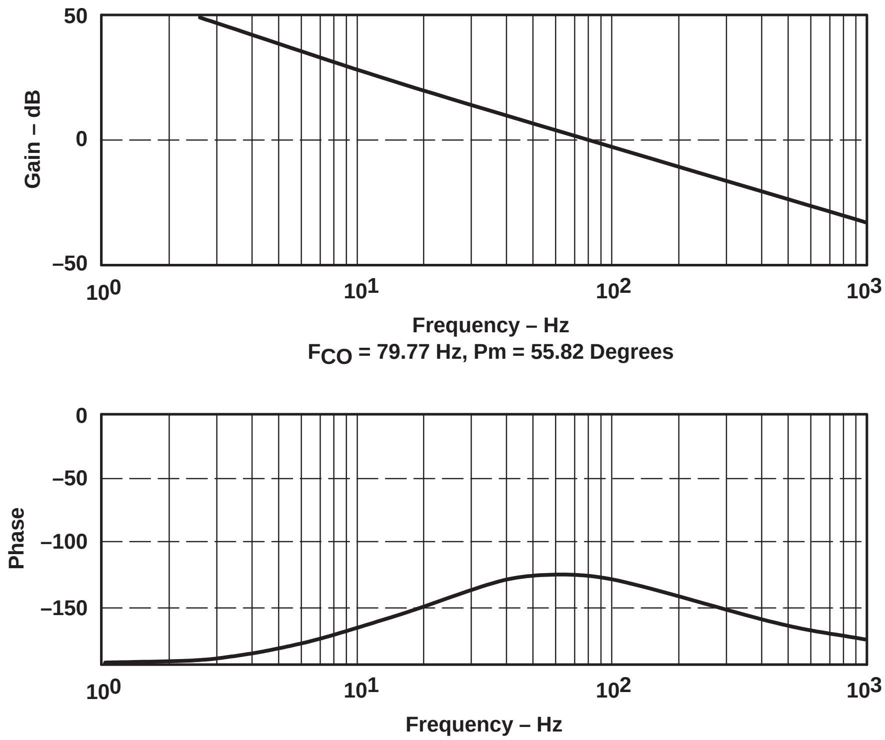


Figure 10. Open-Loop Frequency Response

The open-loop crossover frequency is 79.66 Hz and the phase margin is greater than 55 degrees; therefore, the design goals have been met.

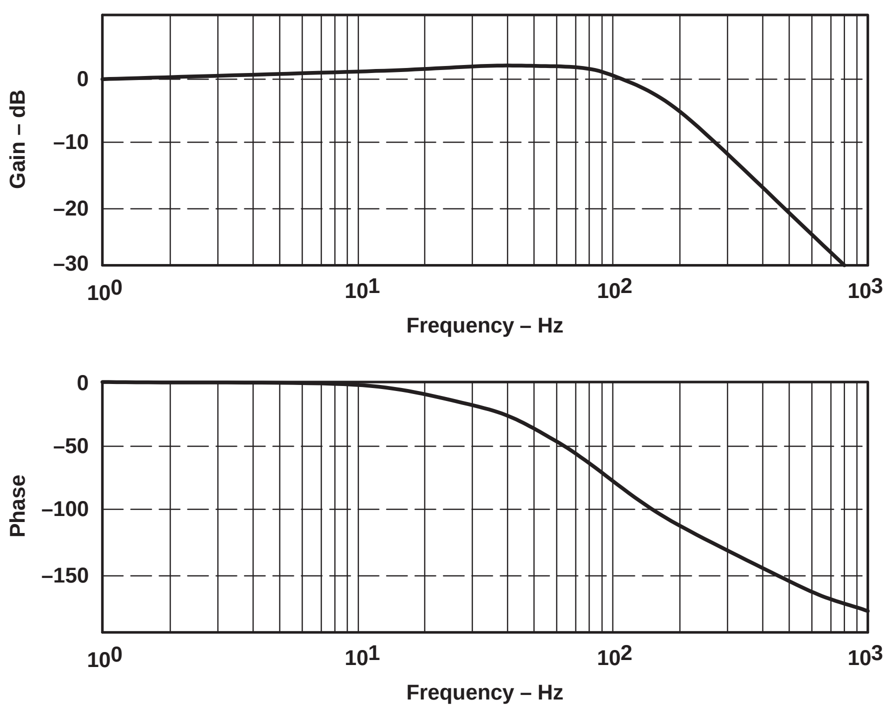


Figure 11. Closed-Loop Frequency Response

Summary

The TLS223x uses a PLL to commutate the spindle motor. The PLL depends on the selection of compensation values for its bandwidth and phase margin. The external components of the TLS223x determine the compensation values. These components provide the capability to adjust the PLL so that it provides optimum performance. The external capacitor that connects to the C_{VCO} pin of the TLS223x sets the gain of the VCO, and advances the commutation state. The bandwidth range for the PLL is 40–100 Hz. The phase-error filter network, external to the PLL, is two capacitors (C_1 and C_2) and a resistor that determines the frequency response for the PLL.