

# Setting the P-I Controller Parameters, KP and KI

Application Note

TLE7242 and TLE8242

Automotive Power



Never stop thinking

## 1 Abstract

*Note: The following information is given as a hint for the implementation of the device only and shall not be regarded as a description or warranty of a certain functionality, condition or quality of the device.*

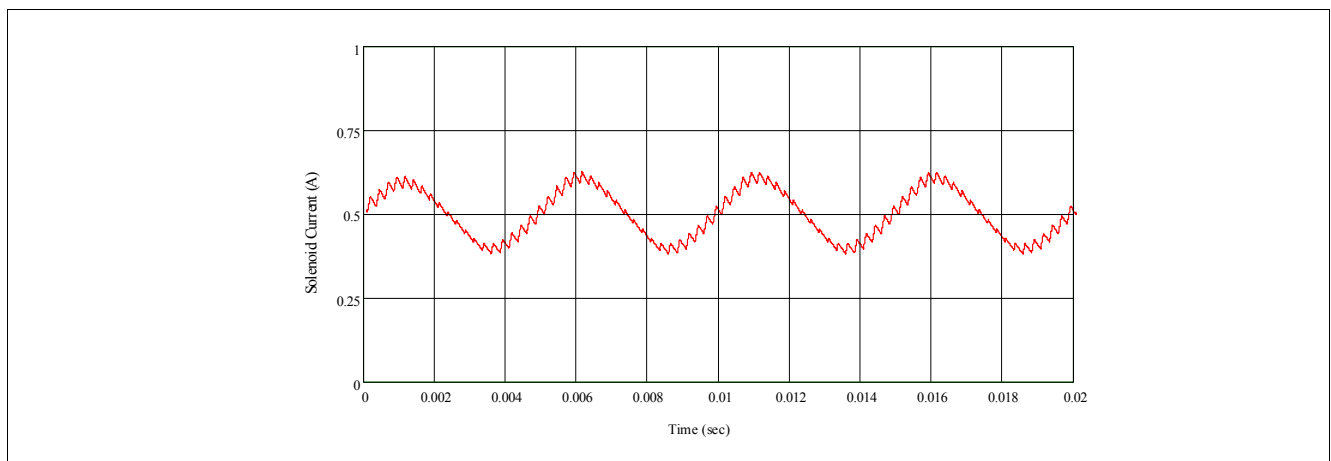
This Application Note is intended to provide a method for determining the proportional gain, KP, and the integral gain, KI, of the Proportional-Integral (P-I) controllers integrated in the TLE 7242 integrated circuit. These methods can also be used to determine the KP and KI values for the TLE 8242 integrated circuit. General information about the TLE7242 can be found in the TLE7242 G datasheet. General information about the TLE8242 can be found in the TLE8242 L datasheet.

## 2 Introduction

The TLE7242 is a four channel pre-driver IC designed to control proportional solenoid valves. Control and diagnostic information are transferred to and from the device using a standard SPI interface.

This device in conjunction with the necessary external components and the solenoid valve form a closed loop control system. The closed loop control system is used to ensure precise current control in the presence of system disturbances and varying component parameter values. The control system uses a fixed PWM frequency in contrast to a hysteretic mode controller which has a variable PWM frequency.

The TLE7242 regulates the current flowing in the solenoid valve over a current range of 0A to 1.2A (typical when a 0.2 Ohm sense resistor is used) with 11 bit resolution. The solenoid valve generally controls either the pressure of the hydraulic fluid at the output of the valve, or the flow rate of the hydraulic fluid through the valve. The device also can add a triangular dither signal to the current to reduce the mechanical hysteresis of the solenoid valve. This triangular waveform is filtered somewhat by the control loop, resulting in a quasi-sinusoidal waveform as shown in Figure 1. The frequency and amplitude of the dither waveform as well as the mean current value are programmed via SPI.

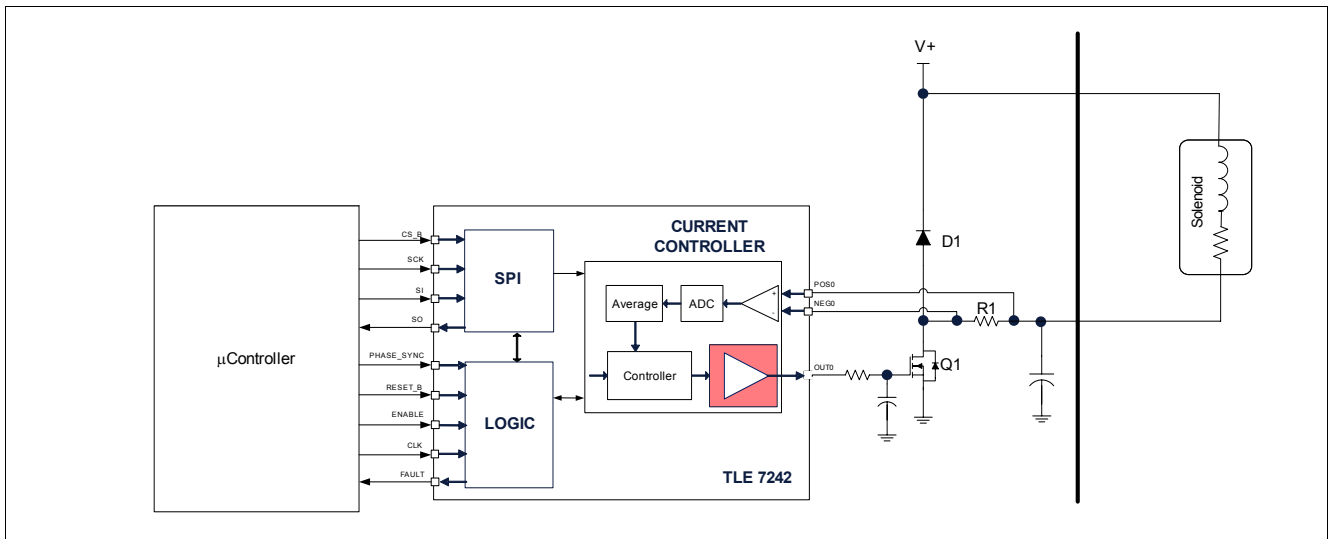


**Figure 1 Typical Current Waveform**

Each channel of the IC includes a P-I controller with programmable gain values KP and KI. Implementing the control law in the current control device can result in improved performance compared to a software implementation, and can reduce the performance requirements of the microcontroller.

This document will describe the TLE7242 G based current control system, show a linear continuous-time model of the system, and present a method to choose the values of KP and KI for a given set of application conditions. The effects of the current control system on the superimposed dither waveform will also be described. Finally, the predictions of the model will be compared to measurements to demonstrate the validity of the model.

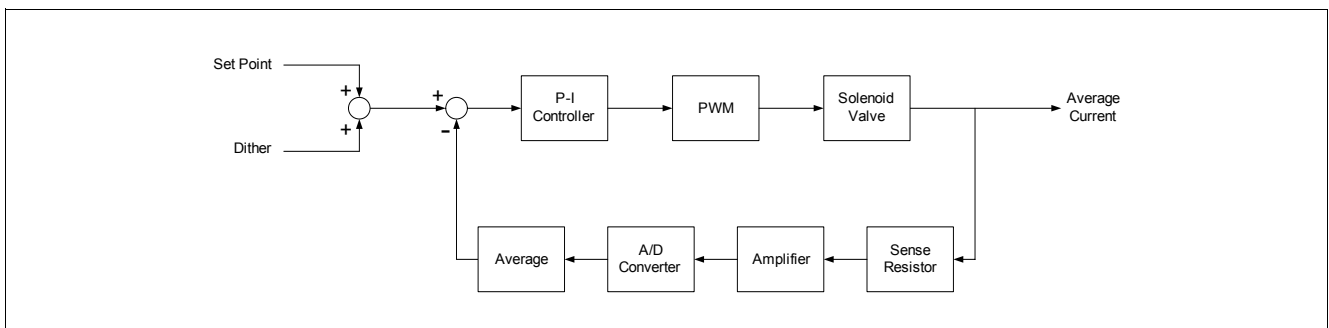
### 3 The TLE7242G Current Control System



**Figure 2 Schematic of the TLE7242 current control circuit**

The schematic in Figure 2 shows the TLE7242 G current control circuit. The input to the current regulation circuit is a digital setpoint message transferred from the microcontroller to the TLE7242 via the SPI interface. The feedback is generated by the sense resistor, R1, and the differential amplifier connected to the POS and NEG pins of the IC. The output of the amplifier is digitized by an A/D converter, averaged over a switching cycle, and compared to the digital setpoint. The P-I controller converts the resulting error signal into a fixed frequency, variable duty cycle signal which is used to control the gate of the external MOSFET, Q1. The current flowing in the solenoid valve (which is the “plant” in this control system) is proportional to the duty cycle of the gate drive signal of MOSFET Q1. The recirculation diode, D1, conducts the solenoid current during the time that the MOSFET is turned off.

Figure 3 shows an equivalent block diagram of the TLE7242 based control system. Note that the dither waveform is added to the average current setpoint at the input of the control system. The PI controller converts the difference in the digital setpoint and the digital output of the averaging block into a digital output control signal. This digital value is converted to a pulse-width modulated (PWM) signal by the PWM block. The solenoid valve ultimately converts the PWM drive signal to an average current value which is the output of the system. The average current is measured and converted to a digital value by the blocks in the feedback path shown in Figure 3.



**Figure 3 Control Diagram of TLE 7242 Based Current Control System**

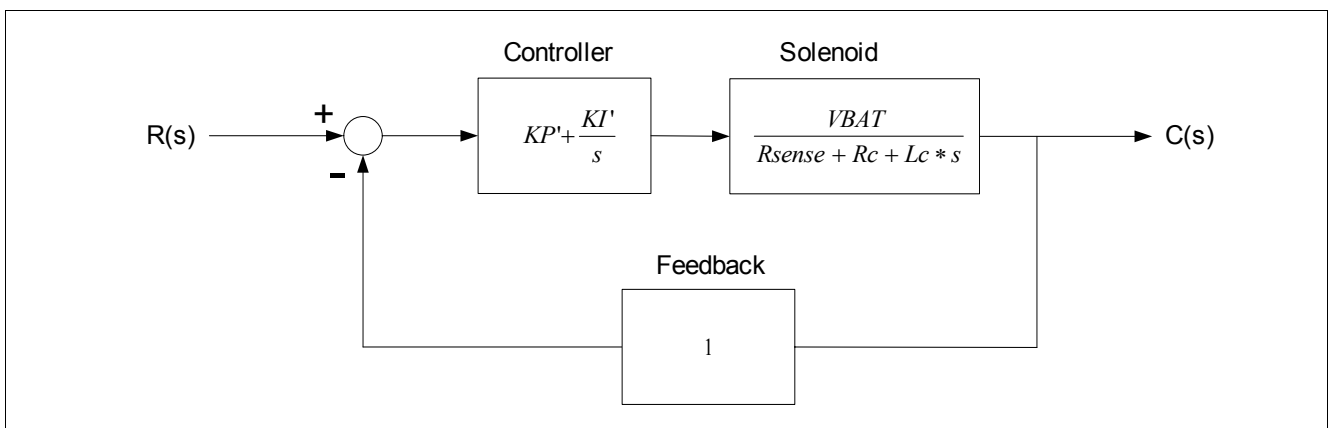
## 4 A Linear Continuous-Time Model

### 4.1 Description

In this section a linear continuous-time model of the control system is presented.<sup>1)</sup> Although the actual control system contains non-linear elements (e.g. saturation effects) and is a discrete time or sampled data system, the model developed here is useful for determining reasonable values of KI and KP for a given application.

The dynamic model is shown in Figure 4 in Laplace transform format. The KP' and KI' gains are the linear model gain terms. The transfer function of the solenoid valve is given as a linear relationship between the VBAT voltage (solenoid supply voltage), the solenoid resistance and inductance and the value of the sense resistor. The actual solenoid valve transfer function contains non-linearities, but the linearized transfer function is a useful approximation.

The output C(s) is the average solenoid current in units of Amps. The input R(s) is the average current setpoint combined with the dither signal, also in units of Amps. The actual system contains scaling in the feedback loop, in the model, however, this scaling has been transferred to the values of KP' and KI' so that the transfer function of the feedback block is simply "1". The actual system will also exhibit a time delay in the feedback path equivalent to  $1/F_{PWM}$ . This delay is not accounted for in this model, but can be neglected when the time constant of the closed loop system response is sufficiently slower than the PWM period (which is also the sample period of the controller).



**Figure 4 Control Diagram of TLE7242 Current Control**

The values of VBAT and Rc affect the transfer function of the solenoid valve. The value of VBAT affects the open loop gain at a given frequency, and the value of Rc (solenoid coil resistance) affects both the location of a pole in the open loop transfer function and also the open loop gain. Both of these values generally will change over a defined range in the application depending on the operating conditions and manufacturing tolerances. The system designer should either design the control system (i.e. choose KI and KP gains) to give acceptable performance over the expected ranges of these two variables, or program different sets of KI and KP values depending on the operating conditions of the system.

<sup>1)</sup>Reference Ogata, Katsuhiko, *Modern Control Engineering*, Englewood Cliffs, NJ, Prentice-Hall Inc. 1970

## 4.2 Open Loop Frequency Response

The open loop transfer function of the model is shown in equation (1).

$$GH(s) = \frac{VBAT}{Lc} \times KP' \times \frac{s + \frac{KI'}{KP'}}{s \times (s + \omega c)} \quad (1)$$

$$\omega c = \frac{(Rsense + Rc)}{Lc} \quad (2)$$

It is evident that the open loop transfer function contains two poles and one zero. The poles are located at  $\omega=0$  and  $\omega=\omega c$  where  $\omega c$  is the frequency associated with the solenoid valve and is defined in equation (2). The zero is located at  $\omega = KI'/KP'$ . The constant multiplier in the open loop transfer function,  $K_{OL}$ , is given in equation (3).

$$K_{OL} = \frac{VBAT}{Lc} \times KP' \quad (3)$$

The location of the poles are generally fixed in the application, and cannot be influenced by the system designer. The system designer can affect the closed loop frequency response of the control system by changing the location of the zero and the value of the factor  $K_{OL}$ . The Bode plots of the open loop transfer function of an example system are shown in Figure 5. The X axis is the ratio of  $\omega$  to  $\omega c$ . The location of the poles are at 0 and 1 on this scale. The location of the zero in this example is marked with the dashed line. The phase plot shows that the closed loop system is stable as the phase shift is always  $<180^\circ$ .

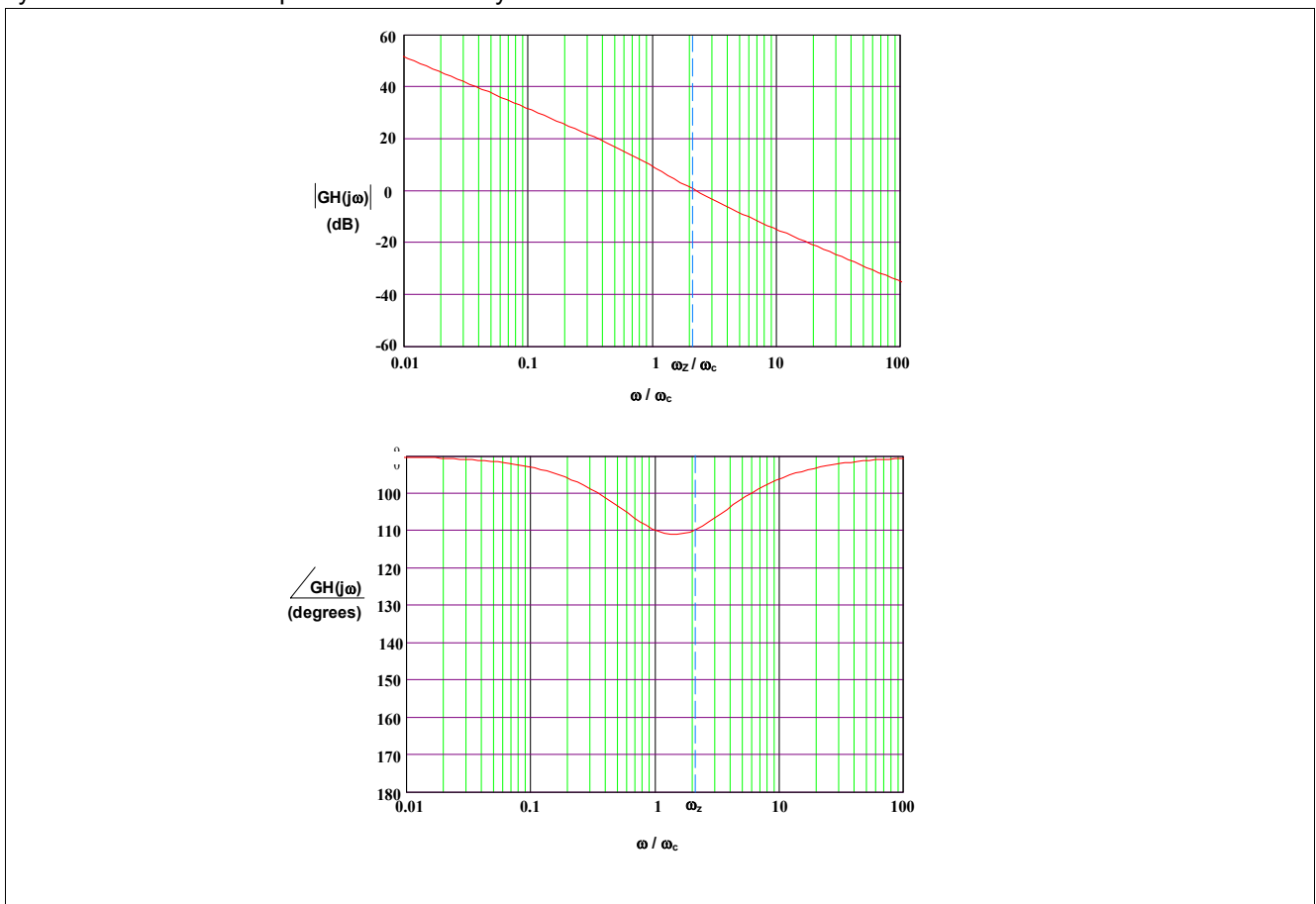


Figure 5 Open Loop Bode Plot - Example

The system parameters used in this example are

- $V_{BAT} = 14V$
- $R_c = 5.6 \text{ Ohm}$
- $L_c = 10 \text{ mH}$
- $R_{sense} = 0.2 \text{ Ohm}$
- $f_{CLK} = 20 \text{ MHz}$
- $f_{PWM} = 4 \text{ KHz}$

## 5 Calculating the values of KP and KI

### 5.1 Setting $\zeta$ and $\omega_n$

Although the control system is not a true low-pass second order system due to the presence of the open loop zero, the parameters  $\zeta$  and  $\omega_n$  as defined in the second order system open loop transfer function shown in equation (4) can be used to estimate the response of the TLE7242G control system. The parameter  $\omega_n$  is the undamped natural frequency of the control loop and  $\zeta$  is the damping ratio of the system.

$$G_{CL}(s) = \frac{K}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (4)$$

The  $\zeta$  value is set to 0.707 in this guide. The value 0.707 generally results in a step response with fast settling time and reasonable overshoot. Increasing the value within the range from 0.707 and 1 will reduce the overshoot of the step response, but will increase the settling time.

The value of  $\omega_n$  is set according to the equation (5). This equation sets the time constant of the closed loop transient response to a value 5 times greater than the sample period of the controller ( $1/f_{PWM}$ ). The time constant of the system can be estimated by the equation (6). The factor of 5 is a minimum value that results in good correlation between the continuous-time model and the actual discrete-time system. The ratio of  $f_{PWM}$  to  $1/t_D$  can be set to values greater than 5, but values less than 5 should be avoided.

$$\omega_n = \frac{f_{PWM}}{5\zeta} \quad (5)$$

$$t_D = \frac{1}{\zeta \times \omega_n} \quad (6)$$

### 5.2 Calculating the values of KP' and KI'

Once the values of  $\zeta$  and  $\omega_n$  are defined, the values of the KP' and KI' are calculated according to the equations (7) and (8).

$$KP' = \left(2\zeta\omega_n - \frac{R_c}{L_c}\right) \times \frac{L_c}{V_{bat}} \quad (7)$$

The unit of KP' is  $[A^{-1}]$  if the units of  $\omega_n$  is  $[s^{-1}]$ ,  $R_c$  is  $[\Omega]$ ,  $L_c$  is  $[H]$  and  $V_{bat}$  is  $[V]$ .

$$KI' = \frac{L_c}{V_{bat}} \times \omega_n^2 \quad (8)$$

The unit of KI' is  $[A^{-1}s^{-1}]$  if the units of  $\omega_n$  is  $[s^{-1}]$ ,  $L_c$  is  $[H]$  and  $V_{bat}$  is  $[V]$ .

If the calculated value of KP' is less than 0, the PWM frequency,  $f_{\text{PWM}}$ , must be increased in order to increase the ratio of the PWM frequency and the frequency of the open loop pole due to the solenoid coil.

### 5.3 Calculating the values of KP and KI

The values of KI and KP, which are the actual values programmed into the TLE7242, can now be calculated according to equations (9) and (10).

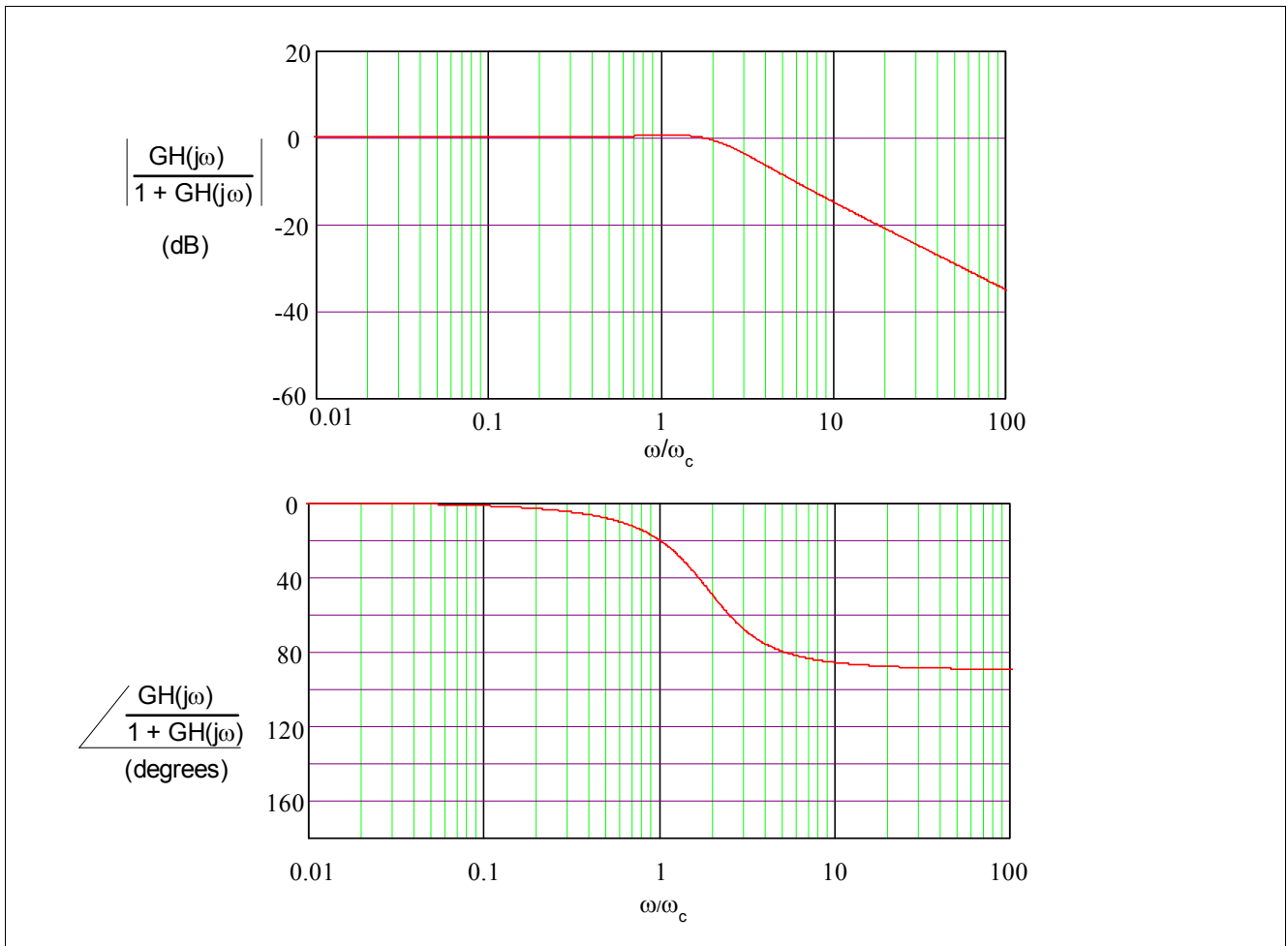
$$KP = KP' \times \frac{0.04 \times f_{\text{CLK}}}{R_{\text{sense}} \times f_{\text{PWM}}} \quad (9)$$

$$KI = KI' \times \frac{0.04 \times f_{\text{CLK}}}{R_{\text{sense}} \times (f_{\text{PWM}})^2} \quad (10)$$

Note: The parameters KP and KI as defined in equations (9) and (10) are unitless. The factor 0.04 in the equations has the unit of Volt,  $R_{\text{sense}}$  has the unit of  $\Omega$ ,  $f_{\text{clk}}$  has the unit of  $\text{s}^{-1}$  and  $f_{\text{pwm}}$  has the unit of  $\text{s}^{-1}$ .

The SPI bit fields of these two gain values are 12 bit wide, so the KP and KI values are limited to values between 0 and 4095. If the calculated value of KP or KI is greater than 4095, the value of  $\omega_n$  must be reduced to a value which results in KI and KP values within the required range.

## 6 Closed Loop Frequency Response



**Figure 6 Closed Loop Bode Plot**

The closed loop response, as predicted by the model, of an example system is shown in Figure 6. The closed loop response shows that the bandwidth of the system is approximately  $4 \times \omega_c$ . The dither signal should be set to a frequency less than this value so that the dither amplitude is not significantly attenuated.



Closed Loop Frequency Response

The model predicts that the gain of the closed loop transfer function is 0.5 at  $\omega=4 \times \omega_c$ . So if the dither frequency is set to  $4 \times \omega_c$ , the dither amplitude will be attenuated by 50%. The Figure 7 shows the measured dither amplitude is 100 mApp at this frequency when the commanded dither amplitude is 200 mApp.

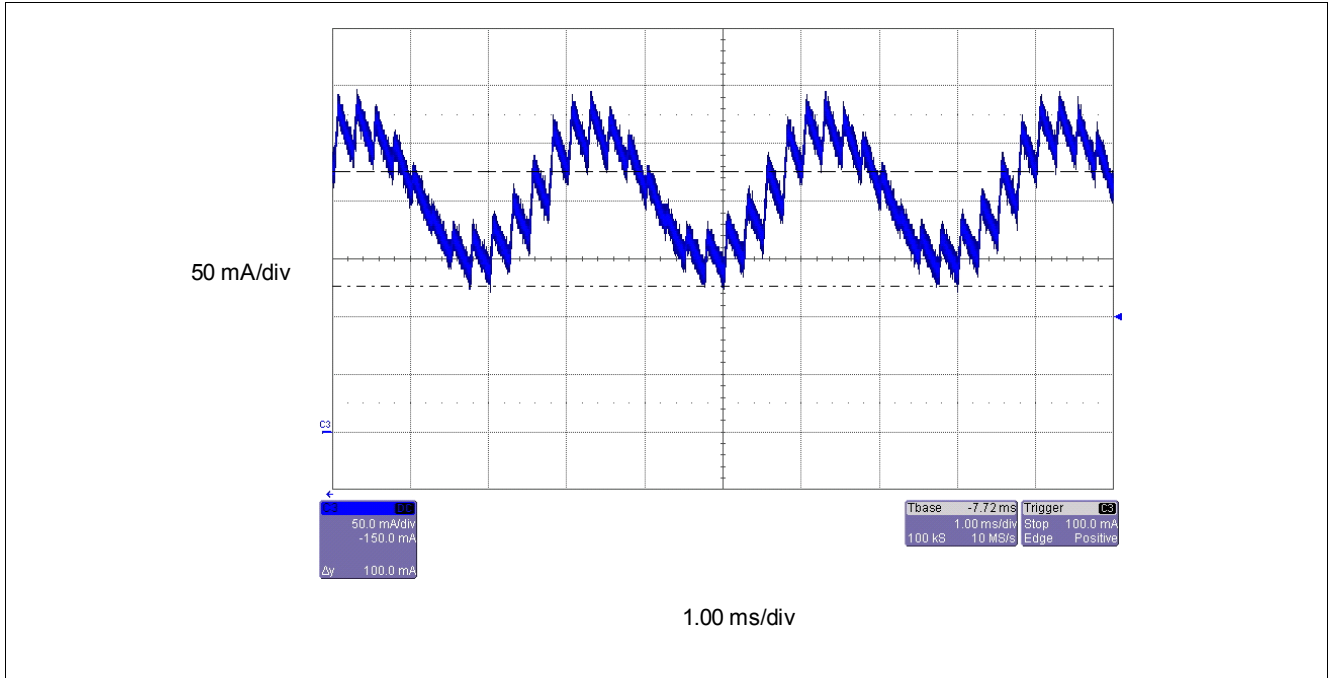
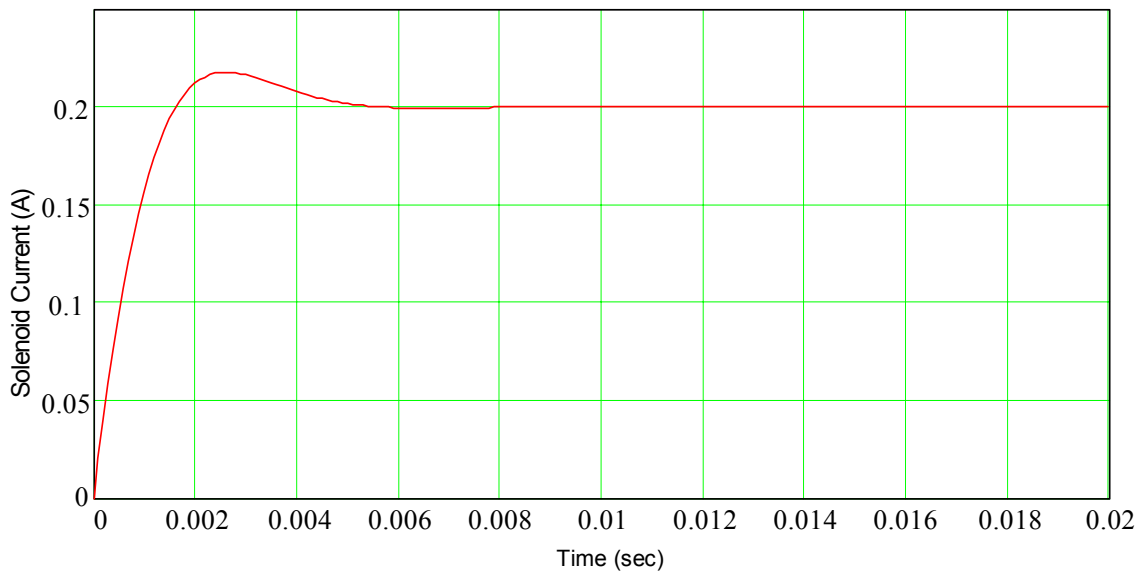


Figure 7 Dither Waveform (Attenuation)

## 7 Comparison of Model Predictions and Measurements

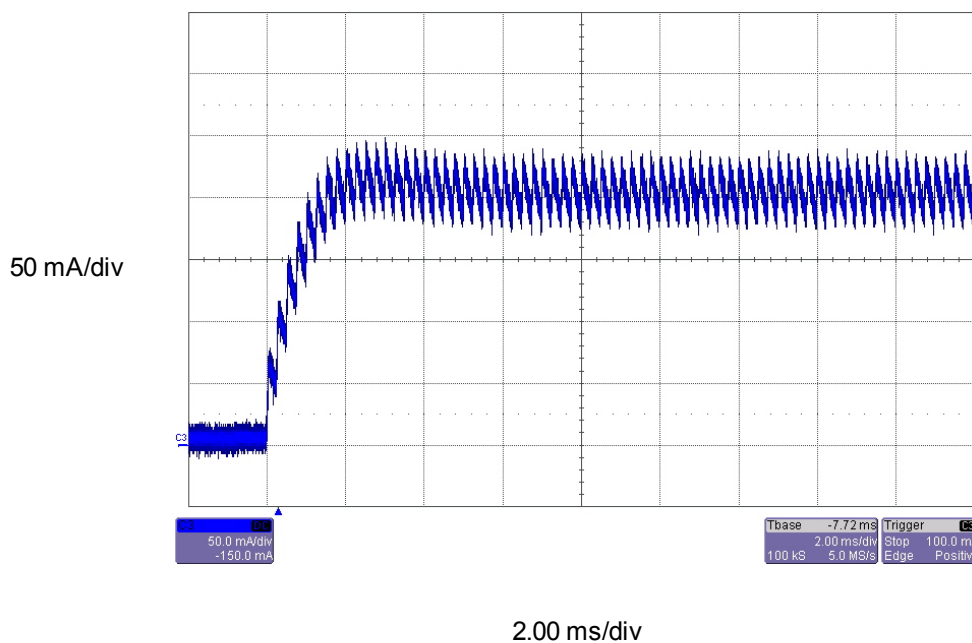
In this section, the simulation results from the linear model are compared to laboratory measurements.

Figure 8 shows the predicted step response of the example system. The setpoint is stepped from 0 mA to 200 mA and the predicted average solenoid current is plotted with respect to time.



**Figure 8** Transient Step Response - Using Linear Model

The actual step response of this system is shown in Figure 9.



**Figure 9** Transient Step Response - Measurement

By comparing Figures 8 and 9 it is clear that the predicted step response and the measured step response are in close agreement. The settling time of this system is in the neighborhood of 5.0 ms.

## 8 Summary

The following system variables are needed

- $V_{BAT}$  Solenoid Supply Voltage
- $R_c$  Solenoid Coil Resistance
- $L_c$  Solenoid Coil Inductance measured at the PWM frequency
- $R_{sense}$  Sense Resistor Value
- $F_{CLK}$  Master Clock Frequency Applied to the CLK pin of the IC
- $F_{PWM}$  PWM Frequency of the Channel

### 1) Set $F_{PWM}$

The maximum  $F_{PWM}$  frequency which should be chosen is 4 KHz. In general, this parameter should be set at this upper limit unless there are specific system requirements which dictate a lower value.

### 2) Set $\zeta$

- $\zeta=0.707$  is generally a good starting point
- increase up to  $\zeta=1$  to reduce overshoot
- decrease  $\zeta$  to improve rise time, but with additional overshoot and ringing

### 3) Calculate $\omega_n$

$$\omega_n = \frac{F_{PWM}}{5\zeta} \quad (11)$$

- decreasing  $\omega_n$  will reduce the bandwidth of the control system, resulting in longer settling times and increased dither amplitude attenuation
- increasing  $\omega_n$  beyond the recommended value will lead to poor matching of the response of the linearized model to the actual system. This is due to effect of sampling on the frequency response of the system.

### 4) Calculate $KP'$

$$KP' = \left(2\zeta\omega_n - \frac{Rc}{Lc}\right) \times \frac{Lc}{Vbat} \quad (12)$$

5) if  $KP' < 0$ , the PWM Frequency must be increased

### 6) Calculate $KI'$

$$KI' = \frac{Lc}{Vbat} \times \omega_n^2 \quad (13)$$

### 7) Calculate KP and KI

$$KP = KP' \times \frac{0.04 \times F_{CLK}}{Rsense \times F_{PWM}} \quad (14)$$

$$KI = KI' \times \frac{0.04 \times F_{CLK}}{Rsense \times (F_{PWM})^2} \quad (15)$$

8) If KP and/or KI are greater than 4095, reduce  $\omega_n$  and return to step 4

## 9 Conclusions

The KI and KP parameters of the TLE7242 G can be calculated according to the guidelines given in this application note. The system designer can choose the values of  $\zeta$  and  $\omega_n$  as suggested in this note, or according to the system requirements. The linear model presented in this application note predicts the behavior of the actual system to an acceptable level of accuracy as long as the PWM period,  $1/F_{PWM}$ , is chosen to be at least 5 times faster than the time constant of the closed loop system as predicted by equation (12).

$$t_D = \frac{1}{\zeta \times \omega_n} \tag{16}$$

Once the values of  $\omega_n$  and  $\zeta$  are chosen, the required values of KP and KI can be calculated according to the equations given in this note. The attenuation of the dither signal amplitude due to the frequency response of the closed loop transfer function can be predicted.

The equations presented in this application note are also the basis of an EXCEL spreadsheet which can be used to quickly select values of KP and KI for an application. Contact your local Infineon representative for a copy of the spreadsheet.

### Limitations

The method presented in this Application Note is based on an assumption that the solenoid valve load can be modeled as an ideal resistor and an ideal inductor in series. In reality, the electrical behavior of a typical solenoid does not follow this model exactly. In some cases, a more complex electrical model of the solenoid may need to be developed in order to adequately calculate the KP and KI values.

## 10 Revision History

### Setting the P-I Controller Parameters, KP and KI

#### Revision History: V2.0, 2009-10-12

Previous Version(s):

Page	Subjects (major changes since last revision)
	Corrected equations 9, 10, 14, and 15
	Added comments that the Fpwm to 1/td ratio can be set to values greater than 5, but values less than 5 should be avoided.

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