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# ADVANTAGES OF FILTERS ON THE INPUT AND OUTPUT TERMINALS OF THE CURRENT-SENSE AMPLIFIER

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## ABSTRACT

This application note provides recommendations for the use of filters on the input and output terminals of the current-sense amplifiers in Allegro motor-gate drivers. Because a current-sense amplifier can amplify differential input voltage and enable programmable gain, selection of an incorrect value for any filter component can introduce undesired offset voltages and gain errors, which can compromise the accuracy of the current-sense amplifier.

## INTRODUCTION

Several error sources can affect a current-sense amplifier. These error sources can be categorized as:

- **Offset Error:** Input offset voltage ($V_{IOS}$), common-mode rejection ratio (CMRR), and power-supply ripple-rejection ratio (PSRR) all create an offset voltage at the input terminals of the sense amplifier. In general, at low input voltage levels, the offset error is the dominant error type of the sense amplifier.
- **Gain Error:** The gain error and linearity of the sense amplifier, coupled with the tolerance of the current shunt resistor, generates errors that vary with input voltage level. In general, at high input voltage levels, the gain error is the dominant error type of the sense amplifier.
- **Application-Dependent Error:** This includes error induced by external circuits and operating conditions. As the name suggests, the influence of this type of error can vary significantly across different gate-driver devices and applications.

This application note highlights the limitations of using filters on the input and output terminals of the sense amplifier used in an Allegro gate driver. Because Allegro gate-driver current-sense amplifiers are capable of amplifying differential input voltage via programmable gain, extra care should be taken when employing filters on the inputs and output terminals of the current-sense amplifier. Incorrect selection of input-filter components can increase input-offset error, introduce gain error, and affect the time response of the sense-amplifier disconnect detection technique. Any filter on an output terminal of a current-sense amplifier should be carefully selected to ensure the sense amplifier output settling time remains within the guaranteed datasheet limits of a given Allegro gate driver.

## SENSE-AMPLIFIER DESCRIPTION

Motor-control applications require accurate and fast current sensing with minimal torque ripple and the ability to achieve minimal audible noise. For accurate current sensing, it is important to have the best dynamic performance of the motor controls. To achieve the best dynamic performance and low acoustic noise in a motor driver in an automotive application, such as electric power steering motor controls, accurate torque control is required. Any inaccuracy of current sensing can lead to distorted current waveforms and, thus, produce torque ripple and, in turn, inefficient and noisy performance. Control of the power-bridge circuit requires knowledge of the actual motor-load current. Thus, different approaches can be used to sense the current of motor-phase windings, including use of power-bridge-leg current sensing or common current to ground sensing using a single current shunt. Allegro devices include a low-side current-sense amplifier with programmable gain and offset. Current-sense amplifiers are specifically designed for current sensing in the presence of high common-mode voltage and current transients. These amplifiers can be employed either independently to provide low-side current measurement in three phases, or they can be used together to provide redundant current sensing. The current-sense amplifier technology in an Allegro gate driver can also check the connections from the current-sense amplifiers to the sensing links using integrated circuits. The low-side current sensing methods employ a shunt resistor placed in the power-bridge leg: When the control-logic inputs of the gate drivers command turn-on of the low-side MOSFETs, the shunt resistor measures the load current flowing through the phase windings.

Reconstruction of the current on three phases requires a single-shunt system that measures the common current to ground and a dedicated sampling technique. The two-shunt current-sensing method uses the principle of Kirchhoff's current law. Kirchhoff's current law allows estimation of the third current using an external microcontroller. In a three-shunt system, the current-sense amplifiers are added to the low-side MOSFETs with a shunt resistor placed in line with each switching leg and, when turn-on of the low-side MOSFETs is commanded, the current is measured on all three branches.

## FILTERS ON SENSE-AMPLIFIER TERMINALS

Allegro gate drivers have programmable gain and programmable-offset sense amplifiers that allow the use of a low-resistance sense resistor or current shunt as a sensing element in the low-side connection of each phase. The input common-mode range of the input terminals allows the below-ground current sensing that is typically required for the low-side current sensing used in pulse-width modulation (PWM) control or for the switching transients of other inductive loads, such as a brushless DC (BLDC) motor or a permanent-magnet synchronous motor (PMSM). The output of the sense amplifier is available at the output terminals of the current-sense amplifier for a given device and can be used in instantaneous or average-current control systems. In an application such as automotive, spikes on the load current might cause the output of the sense amplifier to be noisy, or some overvoltage might occur. This generates either common-mode or differential noise on the input terminals. Consequently, in an automotive application, to improve the accuracy of the current measurement to achieve the best dynamic performance and low acoustic noise for motor controls, it is necessary to filter the current-sense path. The design of any such filter must incorporate components with correctly selected values. Selection of an incorrect filter architecture can lead to undesired offset voltages and gain errors, which can compromise the performance of the sense amplifier. Two filtering techniques can be employed, a common-mode filter and a differential-mode filter, as presented in Figure 1 and Figure 2, respectively.

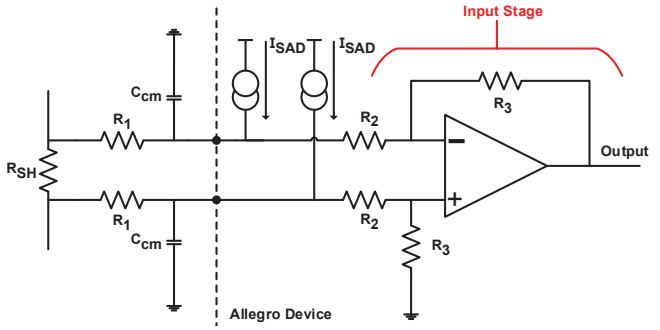


*Figure 1: Common-Mode Filter*

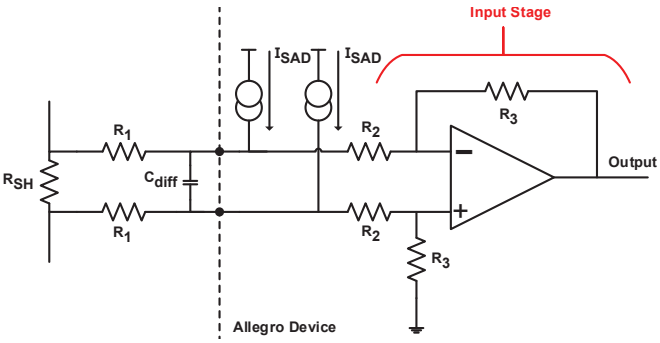


*Figure 2: Differential-Mode Filter*

For more efficient results, the common-mode and differential-mode filtering techniques can be combined. The common-mode filter formed by the $R_1$ and $C_{cm}$ components in Figure 1 can be used to filter out overvoltage or ringing noise, and the differential-mode filter created by the $R_1$ and $C_{diff}$ components in Figure 2 can help to smooth spiky load currents. The cut-off frequency of the input filters must be selected based on the high-frequency voltage oscillations across the current-sense resistor during switching of the low-side MOSFETs. For simplicity, only the common-mode stage or the input stage of an Allegro sense amplifier is shown in Figure 1 and Figure 2. Two continuous current sources ($I_{SAD}$), on the sense amplifier input terminals are also shown in Figure 1 and Figure 2. These continuous current sources are built into Allegro gate drivers, for example, the Allegro A4918, which allows detection of an input open-circuit condition. If an input open-circuit occurs, the voltage increases to greater than the sense amplifier open-load detection threshold ($V_{SAD}$), typically 2 V, and dedicated bits (S1D, S2D, or S3D) for the A4918 gate driver become set in the Verify Result 1 register, depending on the sense amplifier affected.

## FILTERS ON INPUT TERMINALS

Sense-amplifier parameters are provided in Table 1 for the example Allegro A4918 gate driver in an automotive application, where a three-shunt sensing system with a shunt resistor of 0.5 mΩ is used to measure the peak-to-peak motor-load current up to 100 A.

*Table 1: Sense-Amplifier Parameters*

| Parameter | Value | Unit |
|---|---|---|
| Shunt, $R_{SH}$ | 0.5 | mΩ |
| Resistance, $R_1$ | 33 | Ω |
| Typical Resistance, $R_2$ | 54000 | Ω |
| Typical Resistance, $R_3$ | 54000 | Ω |
| Capacitor, $C_{cm}$ | 100 | pF |
| Capacitor, $C_{diff}$ | 100 | pF |
| Current, $I_{PH}$ | ±100 | A |
| PWM Frequency | 16 | kHz |
| Gain, $A_V$ | 20 | V/V |
| Offset, $V_{OOS}$ | 2.5 | V |

The selection of the shunt resistor value of 0.5 mΩ considers the power dissipation and the input offset error voltage ($V_{IOS}$) of the sense amplifier: The value of 0.5 mΩ was chosen to maintain low power dissipation and to provide a differential-amplifier input voltage in excess of the sense-amplifier input offset voltage ($V_{IOS}$) of ±1 mV across the shunt resistor. This reduces the effect of offset error. The selection of the amplifier gain and output offset voltage in this application: ensures that the absolute voltage at the output ($V_{CSXO}$) of the sense amplifier remains within the dynamic range of the amplifier (0.3 V to 4.8 V); and allows the measurement for both positive and negative current flows within the sense resistor ($R_{SH}$). The relationship between the phase current ($I_{PH}$), sense resistor value ($R_{SH}$), and differential amplifier input voltage ($V_{ID}$) can be expressed as:

Equation 1:

$$V_{ID} = I_{PH} \times R_{SH}$$

The absolute sense-amplifier output voltage ($V_{CSXO}$) with respect to ground can be presented as:

Equation 2:

$$V_{CSXO} = (V_{ID} \times A_V) + V_{OOS}$$

The estimated differential amplifier input voltage ($V_{ID}$) ranging between –50 mV and 50 mV obtained from Equation 1 is shown in Figure 3. The estimated sense-amplifier output voltage ($V_{CSXO}$) obtained from Equation 2 remaining within the amplifier dynamic range of 0.3 V to 4.8 V is also shown in Figure 3.

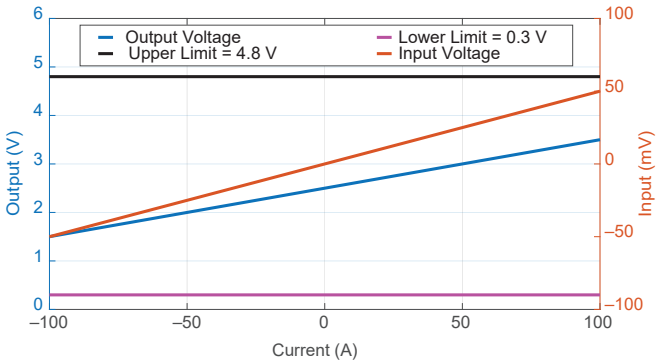


*Figure 3: Input ($V_{ID}$) and Output ($V_{CSXO}$)*

The common-mode filter formed by the $R_1$ and $C_{cm}$ components in Figure 1 can be used to filter overvoltage or ringing noise. Figure 1 shows identical low-pass filters, one placed at each input terminal of the sense amplifier, used to balance the two input terminals. This prevents the introduction of additional offset error. Selection of the $R_1$ resistor and $C_{cm}$ capacitor requires particular consideration. The resistance ($R_1$) can introduce additional input offset error to the specified input offset error voltage ($V_{IOS}$) of the A4918, which is ±1 mV. The additional input offset error can be estimated by considering the specified input offset current ($I_{OS}$) of the A4918 gate driver, which is ±2.3 µA. The input offset current ($I_{OS}$), obtained by measuring the difference between the input bias current at the positive terminal and the input bias current at the negative terminal of the sense amplifier, can be expressed as:

Equation 3:

$$Input\ Offset = R_1 \times I_{OS} = 33\ \Omega \times 2.3\ \mu A = 75.9\ \mu V$$

The estimated additional input offset voltage presented in Equation 3 demonstrates that, with a 33 Ω resistance value on the input terminals of the sense amplifier, the input offset voltage ($V_{IOS}$) of ±1 mV results in an increase of approximately 75.9 µV. This increase represents approximately 7.95% of the input offset voltage ($V_{IOS}$). As the value of the $R_1$ resistor increases, the additional input offset error also increases, as shown in Figure 4. Because the additional input offset error due to $R_1$ resistance becomes amplified by the gain of the sense amplifier, the result is poor accuracy on the output of the sense amplifier. To achieve maintained in-application sense-amplifier accuracy, the recommended value for resistor $R_1$ is generally less than 10 Ω.

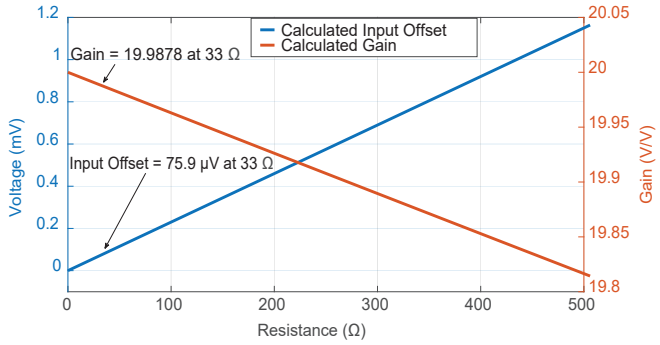


*Figure 4: Input Offset and Gain Errors Due to $R_1$*

The $R_1$ resistance can also introduce gain error on the employed internal programmed gain ($A_V$) of 20 V/V. The modified gain ($A'_V$) due to $R_1$ resistance can be estimated by considering the internal typical sense-amplifier resistors ($R_2$ and $R_3$) and can be expressed as:

Equation 4:

$$A'_V = \frac{R_3}{R_1 + R_2} \times A_V = \frac{54000}{33 + 54000} \times 20 = 19.9878$$

The modified gain ($A'_V$) obtained from Equation 4 proves that, with a resistance value of 33 Ω on the input terminals of the sense amplifier, the internal programmed gain of 20 V/V results in a reduction of approximately 0.0122 V/V. This represents a reduction of almost 0.061%, as shown in Figure 4. However, because the value of the $R_1$ resistor is small in this application, the reduction might be negligeable. Nevertheless, as the value of the $R_1$ resistor increases, the internal programmed gain decreases. This is also shown in Figure 4. Thus, when selecting the $R_1$ resistor, extra consideration is recommended to ensure the gain reduction is as minimal as practicable.

The differential-mode filter created by the $R_1$ and $C_{diff}$ components in Figure 2 can be used to smooth spiky motor-load currents. It is also important to consider that, due to the mismatch caused by the tolerance of the components of the common-mode filter (capacitor $C_{cm}$ and resistor $R_1$), the low-pass-filter cutoff frequency might exhibit slight variations from the two input terminals of the sense amplifier. This can result in an additional error, which can become amplified by the current-sense amplifier. For resistor $R_1$ and capacitors $C_{cm}$ and $C_{diff}$, low-tolerance values are generally recommended, for example, generally 0.5%, 10%, and 5% tolerance for the $R_1$, $C_{cm}$, and $C_{diff}$ filter components, respectively. Depending on the application and customer requirements, differential capacitor $C_{diff}$ can be employed to compensate for the mismatch of the input terminals.

## FILTERS ON OUTPUT TERMINALS

To filter the high-frequency noise that is typical of motor commutation, induced by external circuits and operating conditions, a capacitor filter is typically recommended for use on the output terminals of the current-sense amplifier. Thus, there is a need for a capacitor filter ($C_{out}$) on the output terminals of the sense amplifier, as presented in Figure 5. For the sake of completeness, Figure 5 also shows the input filter of the sense amplifier for the A4918 gate driver created by the common-mode and differential-mode filters. Figure 5 illustrates capacitor filter $C_{out}$ connected on the output terminals after the output stage of the sense amplifier. However, the architecture of capacitor filter $C_{out}$ should be selected to maintain the sense-amplifier output settling time within the guaranteed datasheet limits of a given device. A capacitor filter value of 100 pF was employed for $C_{out}$ in this application, illustrated in Figure 5. The maximum settling time of 1 µs for the A4918 sense amplifier is specified with a $C_{out}$ capacitance of 50 pF. Thus, connecting a $C_{out}$ capacitor of 100 pF to the output terminals of the sense amplifier increases the output settling time to approximately 2 µs, which is not within the guaranteed maximum settling time limit of 1 µs.

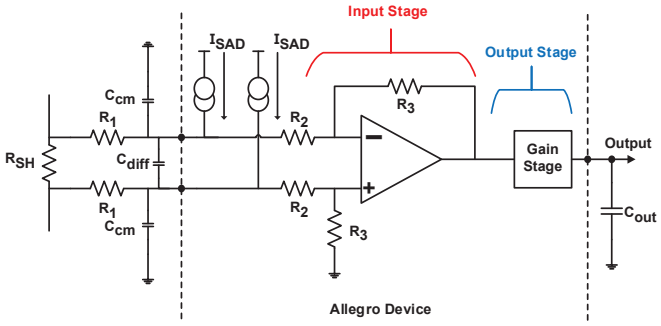


*Figure 5: Filters On Input and Output Terminals*

## EXPERIMENTAL RESULTS

Experimental tests were performed to investigate the transient response of the A4918 sense amplifier with and without filters on the input and output terminals. Several experimental tests were performed on the bench using the A4918 gate driver, which has three built-in internal sense amplifiers. The test bench contains a DC power supply, 1 GHz Tektronix scope, TIVP02 Tektronix differential voltage probe, TCP0020 current probe, and A4918 soldered to an Allegro two-layer demonstration board. For the experimental tests, the gain ($A_V$) was set to 20 V/V and the offset voltage ($V_{OOS}$) was set to 2.5 V. Resistor $R_1$ and capacitors $C_{cm}$ and $C_{diff}$ on the input terminals were chosen to be 33 Ω and 100 pF, as presented in Table 1, respectively, and the capacitor ($C_{out}$) on the output terminals was selected to be 100 pF. To minimize the parasitic inductance of the package during experimental testing, the filter components were selected to fit within a small 0402 footprint.

The transient response of the current-sense amplifier is evaluated with a step change in voltage across the shunt resistor. The sense-voltage step change is obtained by the switch-on of the low-side MOSFETs when the stator-core motor windings are connected to the A4918 gate driver. This causes the winding current to flow through the shunt resistor. The output signals of the A4918 gate driver—GHA, GLA, GHB, GLB, GHC, and GLC—are pulse-width modulated at a switching frequency of 20 kHz using a programmed DE0-Nano-SoC Cyclone V FPGA. The results obtained are presented in Figure 6 through Figure 8:

- Figure 6 shows the step response without filters connected to the input terminals of the sense amplifier. The results obtained show oscillations on the differential input signal ($V_{ID}$), typically induced by external circuits and operating test conditions. The measured sense-amplifier output settling time is approximately 0.8 µs for the output current ($V_{CSIO}$) to reach and settle to a steady-state motor-load current of approximately 18.30 A. The measured sense-amplifier output settling time is less than the maximum settling time of 1 µs specified in the A4918 datasheet.

- Figure 7 presents the obtained transient response data with the common-mode and differential-mode filters connected to the input terminals only. The input filters shown in Figure 5 suppress voltage oscillations on the differential input signal ($V_{ID}$) and therefore reduce the measured output settling time to approximately 0.64 µs. For both step-change tests, with and without input filters, the measured sense-amplifier output settling times are less than the maximum settling time of 1 µs specified in the A4918 datasheet. Like the results without a filter presented in Figure 6, the measured sense-amplifier output settling times are less than the maximum settling time of 1 µs specified in the A4918 datasheet.
- Figure 8 illustrates experimental data obtained with only a capacitor filter connected to the output terminals of the sense amplifier. The results show oscillations on the differential input signal ($V_{ID}$), similar to the oscillations observed in Figure 6. These oscillations are typically induced by external circuitries and operating test conditions. The sense-amplifier output settling time for this experimental test was measured to be approximately 1.92 µs for the output current ($V_{CSIO}$) to reach and settle at a steady-state motor-load current of approximately 18.30 A. The measured settling time of 1.92 µs is greater than the maximum settling time of 1 µs specified in the A4918 datasheet. This is caused by the higher value of the capacitor ($C_{out}$) connected to the output terminal of the sense amplifier, as shown in Figure 5.

Thus, the architecture of the filter capacitor on the output terminal of the sense amplifier should be carefully designed to maintain the sense-amplifier output settling time within the guaranteed datasheet limits of a given Allegro device.

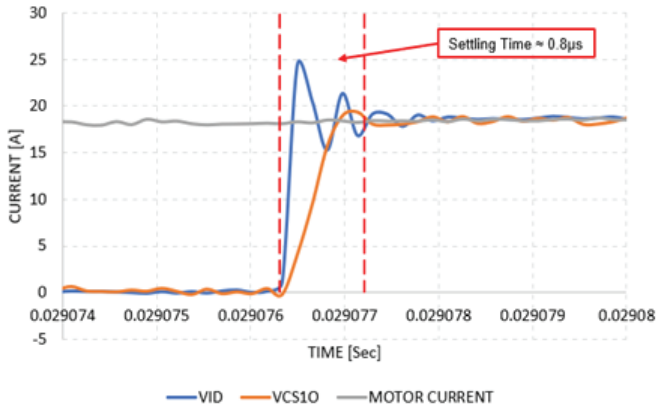


*Figure 6: Transient Response without Input and Output Filters*

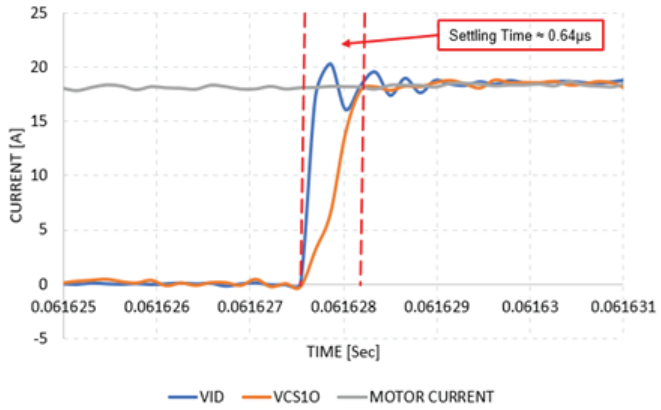


*Figure 7: Transient Response with Input Filters Only*

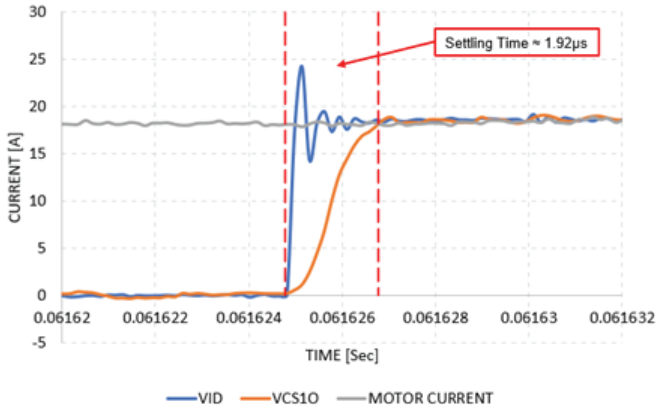


*Figure 8: Transient Response with Output Filter Only*

## CONCLUSIONS

This application note provides information about the effects of filters on the input and output terminals of the current-sense amplifier in an Allegro gate driver used in automotive applications, and provides recommendations for proper selection of filter components. For applications with high common-mode voltage and current transients, specific recommendations are provided for proper design of a filter architecture for filters on the input and output terminals of the current-sense amplifier. The analysis presented in this application note is also valid for the Allegro A4911, A4913, and A4916 gate drivers.

To achieve accurate current measurements for motor-control applications, the following guidelines are recommended:

- To minimize input offset and gain errors, the value of the external resistor ($R_1$) should remain as low as practicable. In general, to ensure that the accuracy of the sense amplifier is acceptable for the application, use of a filter resistor ($R_1$) that is less than 10 Ω is recommended.
- The value of the external resistances and capacitances on the positive and negative input terminals should match. To minimize any additional error that can be caused by any mismatch of the cutoff frequency of the low-pass filter between the two input terminals, use of low-tolerance capacitors is recommended.
- The differential-mode filter created by the $R_1$ and $C_{diff}$ components should be carefully selected such that it mitigates the problematic frequency band.
- Any filter on the output terminals of the sense amplifier should be selected such that the output settling time of the employed current-sense amplifier is maintained within the guaranteed datasheet limits of a given device.
- To reduce oscillations on the differential input signal ($V_{ID}$) of the current-sense amplifier, a shunt resistor ($R_{SH}$) with minimum parasitic inductance should be considered.

*Revision History*

| Number | Date | Description | Responsibility |
|---|---|---|---|
| – | January 20, 2026 | Initial release | K. Tshiloz |

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