Shunt Resistors, High-Performance Op-Amps, Zener Diodes

Low-Side Current Sensing Circuit Design

In the areas of automotive and industrial equipment, low-side current sensing circuits are used for functions including current (voltage) control, over current limiting, and remaining battery level detection. The low-side current sensing circuits, which are achieved with a shunt resistor, an op-amp, and external components, can be incorporated most simply at a lower cost compared with other methods. This application note explains the criteria for selecting parts and determining circuit constants for the low-side current sensing circuits.

Low-side current sensing circuit

Figure 1 shows a typical low-side sensing circuit. Load current ($I_{LOAD}$) from load (LOAD) via the shunt resistor ($R_{SHUNT}$) causes a voltage drop ($\Delta V_{SHUNT}$). This voltage is differentially amplified by the op-amp (OPAMP), connected to an A/D converter, microcontroller, or other devices in the subsequent stage. Then, the current value is measured and used for system control.

![Figure 1. Typical low-side current sensing circuit](image-url)

The symbols in Figure 1 represent the following:
- **OPAMP**: Op-amp
- **LOAD**: Load
- **$I_{LOAD}$**: Load current
- **$R_{SHUNT}$**: Shunt resistor
- **$V_{OS}$**: Op-amp offset voltage
- **$\Delta V_{SHUNT}$**: Shunt voltage
- **$R_{1.1} = R_{1.2} = R_1$, $R_{2.1} = R_{2.2} = R_2$**: Gain setting resistors
- **$C_{1.1} = C_{1.2} = C_1$**: Filter capacitor
- **$D_{1.1}, D_{1.2}$**: Protection diodes
In an ideal circuit where an op-amp without an input offset voltage is used the following equation with the circuit in Figure 1.

\[ V_O = I_{LOAD} \times R_{SHUNT} \times \left( \frac{R_2}{R_1} \right) \] [V] \qquad (1)

In actual circuits, the current sensing error is affected by the input offset voltage of the op-amp, the tolerance of the shunt resistor and the relative tolerance of gain setting resistors \( R_1 \) and \( R_2 \). The output voltage with these considerations \( (V_O') \) can be expressed with the following equation.

\[ V_O' = \left[ I_{LOAD} \times R_{SHUNT}' \times \left( \frac{R_2'}{R_1'} \right) \right] + \left[ V_{OS} \times \left( \frac{R_1' + R_2'}{R_1'} \right) \right] \] [V] \qquad (2)

Where \( R_{SHUNT}' \), \( R_1' \), and \( R_2' \) are the values including the respective tolerances. For the input offset voltage for the op-amp \( (V_{OS}) \), only the positive direction is described for convenience of calculation.

Furthermore, the current sensing error \( (E_{rr}) \) attainable with this circuit can be expressed with the following equation.

\[ E_{rr} = \frac{V_{O'} - V_O}{V_O} \times 100 \] [%] \qquad (3)

How to determine the circuit constants

This section explains how to select the electronic components and determine the circuit constants based on the equations above. First, determine the following items as the required specifications of the current sensing circuit.

- Current sensing range: \( I_{LOAD_{min}} \) to \( I_{LOAD_{max}} \) [A]
- Current sensing error: \( E_{rr} \) [%]
- Current sensing frequency: \( f_{sense} \) [Hz]

The current sensing frequency represents how fast the current can be measured relative to the current variation. If the current sensing speed is too slow, the sensing cannot follow the variation in the load current, leading to incorrect measurement. If the current sensing speed is too fast, noise and other irregularities may be detected, also leading to incorrect measurement. Therefore, it is necessary to define the sensing frequency that matches the time transient of the current to be measured.

- Maximum voltage drops at the shunt resistor: \( \Delta V_{SHUNT_{max}} \) [V]

The current sensing error is falling with increasing voltage drop \( (\Delta V_{SHUNT}) \) at shunt resistor \( (R_{SHUNT}) \). (see Footnote 1). Since voltage drop \( (\Delta V_{SHUNT}) \) of is between load and ground in low-side current sense circuit setup, ground voltage level seems to be raised. This can lead to instability of load circuit.

- Maximum output voltage of the op-amp: \( V_{O_{max}} \) [V]

Determine the specification based on a balance between the maximum voltage which can provided at output of op-amp and the input voltage range that can be accepted by an A/D converter or other devices in the subsequent stage.

After determining the specifications, select the electric components and calculate the constants according to the procedures described in the following pages.
Low-Side Current Sensing Circuit Design

Application Note

Step 1: Selection of the shunt resistor
The shunt resistor value is calculated with Equation (4) based on the required specifications determined above. In addition, since a large current flows through the shunt resistor, it is necessary to pay attention to the power rating. Along with, of course, using the shunt resistor within its own rating, it is recommended that a shunt resistor with a sufficient margin for the power capacity rating should be selected, considering the effect of heat generation by the shunt resistor on the surrounding area. The power rating is calculated with Equation (5). Select a shunt resistor satisfying these conditions.

\[
R_{SHUNT} = \frac{\Delta V_{SHUNTmax}}{I_{LOADmax}} \quad [\Omega] \quad \cdots (4)
\]

\[
P_{SHUNT} \geq \Delta V_{SHUNT} \times I_{LOADmax} \quad [W] \quad \cdots (5)
\]

Step 2: Design of the gain setting resistors
The signal gain is expressed with Equation (6). If either of \( R_1 \) or \( R_2 \) is determined, the resistor value of the other can be calculated.

\[
Gain = \frac{V_{Omax}}{\Delta V_{SHUNTmax}} \quad [V/V] \quad \cdots (6)
\]

\[
= \frac{R_2}{R_1} \quad [V/V] \quad \cdots (7)
\]

Step 3: Selection of the op-amp
When selecting the op-amp, it is necessary to pay attention to the following items.
- Offset voltage. Using Equations (1), (2), and (3), calculate the input offset voltage for the op-amp required to achieve current sensing error \( E_r \).
- The input voltage range of the op-amp must have a margin for \( \Delta V_{SHUNT} \).
- The output voltage range of the op-amp must be wider than the input voltage range of the system in the subsequent stage (for example, an A/D converter or microcontroller).
- The op-amp must be operable with the given system supply voltage.
- The frequency characteristics of the op-amp must be at least approximately 10 times higher than \( f_{sense} \).

Step 4: Design of the frequency characteristics
Value of capacitor \( C_1 \) can calculated with Equation (8).

\[
C_1 = \frac{1}{2\pi \times f_{sense} \times 10 \times R_2} \quad [F] \quad \cdots (8)
\]

Step 5: Other peripheral circuits
- Protection circuit
In Figure 1, Zener diodes are used for over voltage protection on the input terminal of the op-amp in case of an open failure of the shunt resistor. If the shunt resistor opens, a voltage of +12 V at maximum may be applied to the input terminal of the op-amp [+12 V is the same voltage applied to the load (LOAD)]. Therefore, it is necessary to insert protective elements so that the voltage rating of the input terminal of the op-amp is not exceeded. Depending on the circuit protection requirements, it is necessary to design the circuit protection including the protection circuit method and the type of protection diode.
How to determine the circuit constants (design example)

Within next chapter, according to the procedures for selecting the electronic components and setting the constants described in the previous section, select the electronic components and determine the circuit constants.

Assume that the required specifications of the low-side current detection circuit are as follows.

- Current sensing range: $I_{\text{LOADmin}}$ to $I_{\text{LOADmax}} = 30$ A to 50 A
- Current sensing error: $E_r = 7\%$
- Current sensing frequency: $f_{\text{sense}} = 1$ kHz
- Voltage drop at shunt resistor: $\Delta V_{\text{SHUNTmax}} = 50$ mV
- Maximum output voltage of the op-amp: $V_{\text{Omax}} = 3.3$ V

**Step 1: Selection of the shunt resistor**

Value of shunt resistor is determined by substituting the values into Equations (4) and (5) above.

\[
R_{\text{SHUNT}} = \frac{\Delta V_{\text{SHUNTmax}}}{I_{\text{LOADmax}}} = \frac{50\text{ mV}}{50} = 1 \text{ m\Omega}
\]

Shunt resistor power rating

\[
P_{\text{SHUNT}} \geq \Delta V_{\text{SHUNT}} \times I_{\text{LOADmax}} = 50 \text{ mV} \times 50 = 2.5 \text{ W}
\]

In this example, the smallest type is selected from ROHM's shunt resistors.

PSR100 1mΩ, power rating 4 W (at 140°C), size 6.4 mm × 3.2 mm

**Step 2: Design of the gain setting resistors**

Values of resistors $R_1$ and $R_2$ for setting gain is determined with Equations (6) (7). Set $R_1 = 2k\Omega$ and calculate $R_2$.

\[
\text{Gain} = \frac{V_{\text{Omax}}}{\Delta V_{\text{SHUNTmax}}} = \frac{R_2}{R_1}
\]

\[
R_2 = R_1 \times \left(\frac{V_{\text{Omax}}}{\Delta V_{\text{SHUNTmax}}}\right) = 2k \times \frac{3.3}{50m} = 132 \text{ k\Omega}
\]

For circuits where the gain is set with external resistors, it is necessary to consider the relative tolerance of $R_1$ and $R_2$ to determine the gain. Furthermore, to reduce the number of electronic components, select 120kΩ from the E24 series. Chip resistors from ROHM’s series MCR01, MCR03, MCR10, or MCR18 can be selected. For these resistors, the tolerance of the resistor value is Class D ±0.5%, and the temperature characteristics are ±50 ppm/°C (between 100Ω and 1MΩ).

**Step 3: Selection of the op-amp**

The offset voltage of the op-amp required to achieve a current sensing error $E_r$ of 7% or less is derived from Equations (1), (2), and (3). Substitute Equations (1) and (2) into Equation (3), and rearrange it into an equation for calculating $V_{\text{OS}}$. For $R_1'$, $R_2'$, and $R_{\text{SHUNT}}'$, the calculation includes the tolerance of the resistor values and the temperature characteristics of the resistor values. Current sensing error $E_r$ reaches its maximum under the following conditions. Substitute them into the equation to calculate $V_{\text{OS}}$.

\[
R_1' = (\text{Tolerance}) \times (\text{Temperature characteristics}) \times R_1 = (-0.5\%) \times (-50 \text{ ppm/°C}) \times R_1
\]

\[
R_2' = (\text{Tolerance}) \times (\text{Temperature characteristics}) \times R_2 = (+0.5\%) \times (+50 \text{ ppm/°C}) \times R_2
\]

\[
R_{\text{SHUNT}}' = (\text{Tolerance}) \times (\text{Temperature characteristics}) \times R_{\text{SHUNT}} = (+1\%) \times (+100 \text{ ppm/°C}) \times R_{\text{SHUNT}}
\]

\[
V_{\text{OS}} \leq 847\mu \text{ (at } T_A = 125°C) \text{ [V]}
\]

Considering the other characteristics required for the op-amp, in this example ROHM’s LMR1802G-LB is selected.
(Why ROHM’s op-am LMR1802G-LB has been selected is described within Footnote 2.)
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Low-Side Current Sensing Circuit Design

Step 4: Design of the frequency characteristics

Equation (8) is used to calculate filter capacitor \( C_1 \). 150\( \mu \)F is selected from E6 series.

\[
C_1 = \frac{1}{2\pi f_{\text{sense}} \times 10 \times R_2} = \frac{1}{2\pi \times 1k \times 10 \times 120k} = 133 \text{ [pF]}
\]

Step 5: Other peripheral circuits

For the selected op-amp, LM1802G-LB, the rating of the input terminal voltage is 7 V. Furthermore, Zener Voltage \( V_Z \) is set to +5V, the supply voltage of the op-amp. If it is assumed that the shunt resistor is open Current flow through the Zener diodes \( (I_{ZD}) \) is calculated with below equation.

\[
I_{ZD} = \frac{V_{\text{in}} - V_Z}{R_1} = \frac{12 - 5}{2k} = 3.5mA
\]

If a zener diode with 5V Zener voltage and 3.5mA Zener current is required, ROHM’s products can be selected such as TDZV5.1, UDZV4.7B, EDZV4.7B, and CDZV4.7B.

Following example circuit can now set up with calculated and selected electronic components.

![Diagram](image-url)

**Figure 2. Circuit satisfying the required specifications of the Current Sensing Circuit**

**Bill of materials for the designed circuit.**

<table>
<thead>
<tr>
<th>Designator</th>
<th>Electronic component</th>
<th>Product item number</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>Op-amp</td>
<td>LMR1802G-LB</td>
</tr>
<tr>
<td>R_{SHUNT}</td>
<td>Shunt resistor for current sensing</td>
<td>PSR100 1mΩ</td>
</tr>
<tr>
<td>D_{1-1}, D_{1-2}</td>
<td>Zener diodes for op-amp input terminal protection</td>
<td>TDZV5.1, UDZV4.7B, EDZV4.7B, CDZV4.7B, etc.</td>
</tr>
<tr>
<td>R_{1-1}, R_{1-2}</td>
<td>Gain setting resistors</td>
<td>MCR01/03/10/18 series 2kΩ, Class D (±0.5%)</td>
</tr>
<tr>
<td>R_{2-1}, R_{2-2}</td>
<td>Gain setting resistors</td>
<td>MCR01/03/10/18 series 120kΩ, Class D (±0.5%)</td>
</tr>
<tr>
<td>C_{1-1}, C_{1-2}</td>
<td>Capacitors for frequency characteristics</td>
<td>150 pF</td>
</tr>
</tbody>
</table>

Note: For the detailed specifications of each electronic component, refer to the data sheet on the ROHM website.

Table 1. Bill of material
Current sensing error and other characteristics of the designed circuit
At first, current sensing error is to verify. A current sensing error $E_{\text{r}}$ of 7% is to ensure in respect to input offset voltage, tolerance of each electronic component and temperature characteristics. Under the conditions for the input offset voltage for the op-amp, tolerance of the resistor value, and temperature characteristics as described in Table 2, current sensing error $E_{\text{r}}$ is to check.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Input offset voltage $V_{\text{OS}}$ (LMR1802G-LB)</th>
<th>Shunt resistor value $R_{\text{SHUNT}}$ (PSR100)</th>
<th>Gain setting resistors $R_1$ and $R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Typ condition</td>
<td>Typ = 5 µV</td>
<td>Typ value</td>
<td>Typ value</td>
</tr>
<tr>
<td>(2) Only the offset voltage is at maximum ($T_A = 25^\circ\text{C}$)</td>
<td>Max. 450 µV ($T_A = 25^\circ\text{C}$)</td>
<td>Typ value</td>
<td>Typ value</td>
</tr>
<tr>
<td>(3) The offset voltage is at maximum and the tolerance of the resistor value is included ($T_A = 25^\circ\text{C}$)</td>
<td>Max. 450 µV ($T_A = 25^\circ\text{C}$)</td>
<td>Class F (±1%)</td>
<td>Class D (±0.5%)</td>
</tr>
<tr>
<td>(4) The offset voltage is at maximum and the tolerance of the resistor value is included ($T_A = 125^\circ\text{C}$)</td>
<td>Max. 500 µV ($T_A = 125^\circ\text{C}$)</td>
<td>Class F (±1%) +100 ppm/°C</td>
<td>Class D (±0.5%) ±50 ppm/°C</td>
</tr>
</tbody>
</table>

Note: For the temperature characteristics, increase in temperature due to self-heating is not considered. Care must be taken if the parts may generate heat in actual equipment.

Table 2. Calculation conditions for plots in Figure 3

![Figure 3. Current sensing error vs. sensing current value for the designed circuit](image-url)

In the range $I_{\text{LOAD}} = 30$ A to 50 A as set in the specification, the current sensing error is below 7%.

Other characteristics are calculated as follows. It is confirmed that the circuit design can satisfy the required specifications.

Output maximum voltage $V_{\text{omax}} = 3.153$ V [under Condition (4)] $\leq 3.3$ V

Frequency characteristics $f_{\text{sense}} = 8.85$ kHz (Secured 8.85 times the actual operation frequency of 1 kHz.)
Verify with “ROHM Solution Simulator” (free web simulation tool)

Circuit simulation can be done with a free web simulator called “ROHM Solution Simulator”. Since circuit constants can be changed, it is easy to design and verify the optimal circuit for the application.

The following circuits are prepared as low-side current sensing circuits, depending on the simulation parameters.

- **DC Sweep**: DC sweep of the current to be detected, output voltage and gain can be monitored.
- **DC Sweep with offset**: Add offset to check the effect to a current sensing error.
- **Transient Response**: The response of output voltage when current is applied in pulses.
- **Frequency Response**: Frequency characteristics of input terminal to output voltage.

*For more information about the simulation, please refer to the Schematic Information of each simulation circuit page.

*To access the ROHM Solution Simulator, you must be logged in with your MY ROHM account.

Please register for a MY ROHM account.
Thermal Evaluation Result of an actual board

In low-side current sensing circuits that use shunt resistors, operational amplifiers, and external components, the shunt resistors generate heat, so board design is also important. The results of thermal evaluation and simulation of an actual board are shown below. Please refer to the reference design [REFSENS002] for details of the circuit, board pattern, and evaluation data.

Conditions: 100A Current Sense
Shunt Resistor PSR400 2mΩ 4-parallel (0.5mΩ)


![PCB Layout of Reference Design](image)

Figure 5. PCB Layout of Reference Design [REFSENS002]

Experiment content: It fixed the placement of the shunt resistor and the width and length of the pattern, and compared the heat generation by the thermal VIA diameter and placement.

Experimental results: According to the board actual measurement results in Table 3., the layout of heat dissipation vias "via diameter: φ0.3mm, left-right 1.2mm pitch, up-down 2.4mm pitch" results in the least heat generation. In addition, although actual measurements have not been performed, thermal simulation results show that "via diameter: φ0.3 mm, up-down and left-right 2.4 mm pitch" has the lowest heat generation. It can be seen that the design of thermal via diameter and placement is important. The trends of thermal simulation and actual measurement match relatively accurately, and it can be said that the use of thermal simulation is a design method that leads to a reduction in board design man-hours for applications that are sensitive to heat generation.
### Table 3. Simulation and Evaluation result by Thermal VIA diameter and placement

<table>
<thead>
<tr>
<th>Pattern and VIA</th>
<th>Thermal Simulation (100A)</th>
<th>Thermal Evaluation (100A)</th>
</tr>
</thead>
</table>
| VIA diameter: φ0.3mm  
Up-down, Left-right : 1.2mm pitch | ![Simulation Image](image1.png)  
TJ = 91.3°C  
(Diff. from Sim -1.8%) | ![Evaluation Image](image2.png)  
TJ = 89.7°C |
| VIA diameter: φ0.5mm  
Up-down, Left-right 1.2mm pitch | ![Simulation Image](image3.png)  
TJ = 91.1°C  
(Diff. from Sim +0.44%) | ![Evaluation Image](image4.png)  
TJ = 91.5°C |
| VIA diameter: φ0.8mm  
Up-down, Left-right 1.2mm pitch | ![Simulation Image](image5.png)  
TJ = 93.4°C  
(Diff. from Sim -3.6%) | ![Evaluation Image](image6.png)  
TJ = 90.0°C |
| VIA diameter: φ0.3mm  
Up-down 1.2mm pitch,  
Left-right 2.4mm pitch | ![Simulation Image](image7.png)  
TJ = 90.6°C  
(Diff. from Sim -2.3%) | ![Evaluation Image](image8.png)  
TJ = 88.5°C |
| VIA diameter: φ0.3mm  
Up-down, Left-right 2.4mm pitch | ![Simulation Image](image9.png)  
TJ = 89.5°C | — (not measured) |
Summary

How to determine circuit constants, calculating and selecting electronic components for a low side-current sensing circuit is explained within this application note.

ROHM manufactures both shunt resistors and high-performance op-amps that can meet the required specifications of various applications. For the products and product lineups listed in this application note, and for related application notes, refer to the following resources.

The calculation of the current detection accuracy in this application note does not include errors due to the noise characteristics and CMRR characteristics of the operational amplifier. If you need to calculate the accuracy more accurately, please take these factors into account.

<Added in Rev.005>
It conducted a heat generation evaluation on an actual board and showed that it is possible to reduce heat generation depending on the diameter and placement of thermal VIA. It also shows the possibility of using thermal simulation to reduce board design man-hours.

This application note uses an operational amplifier for the current sensing circuit, but ROHM has a lineup of Current Sense Amplifier (CSA) products with built-in gain resistors. The options will expand depending on the required current sensing accuracy, board size, price, etc.

References
Shunt Resistor Press Release: Expanding Lineup of Shunt Resistors Contributes to Miniaturization In High Power Applications
Application Note: Op-Amp/Comparator Tutorial

Related application notes
Shunt resistor : Method of Suppressing Increase in Surface Temperature of Shunt Resistors
Effect of PCB Design on Temperature Coefficient of Resistance

Thermal design : Effect of PCB Design on Temperature Coefficient of Resistance
Basics of Thermal Resistance and Heat Dissipation

Related products
Shunt resistor Lineup of shunt resistors
High-performance op-amp Lineup of high-performance op-amps
Diode Lineup of Zener diodes
Current Sens Amplifier Lineup of Current Sense Amplifier

Related Reference Design
REFSENS002 Up to 100A Current Sensing with Shunt Resistor and OpAmp Reference Design
REFSENS003 Up to 30A Current Sensing with Shunt Resistor and Current Sense Amp Reference Design

History
Jun. ’21 : Rev.001 Draft
Jul. ’21 :Rev.002, 003 typo correction
Oct. ’21 :Rev.004 Add links of ROHM Solution Simulator
Jan. ’23 :Rev.005 Add thermal simulation and evaluation on actual board
Footnote 1

Why is current sensing error falling with increasing voltage drop ($\Delta V_{SHUNT}$) at shunt resistor (RSHUNT)? As can also be seen from Equation (2), the current sensing error depends on the voltage drop at the shunt resistor ($\Delta V_{SHUNT}$) and the input offset voltage for the op-amp ($V_{OS}$).

The sensing error can be improved by selecting an op-amp with a smaller input offset voltage. A balance between the sensing error and the cost or characteristics should be considered.

![Figure 6. Effect of difference in $\Delta V_{SHUNT}$ on the current sensing error](image)

Footnote 2

This footnote explains characteristics of LMR1802G-LB and why this op-amp has been selected. The main characteristics of LMR1802G-LB and the result of their examination against the required specifications are shown below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electrical characteristic</th>
<th>reason for choosing LMR1802G-LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage range</td>
<td>2.5 V to 5.5 V</td>
<td>Operable in the 3.3 V and 5 V systems.</td>
</tr>
<tr>
<td>Output voltage range</td>
<td>$V_{OH} = V_{DD} - V_{OUT}$: Max. 50 mV</td>
<td>If the input voltage range of an A/D converter or other devices in the subsequent stage is set to approximately 4 V and the op-amp is operated in the 5 V system, the circuit can be designed so that $V_O &lt; 4$ V.</td>
</tr>
<tr>
<td></td>
<td>$V_{OL}$: Max. 50 mV</td>
<td></td>
</tr>
<tr>
<td>Input voltage range</td>
<td>Input common-mode voltage range:</td>
<td>When the op-amp is operated normally, the input voltage will be increased only to the $\Delta V_{SHUNT}$ level at the highest, causing no issues.</td>
</tr>
<tr>
<td></td>
<td>$V_{SS}$ to $V_{DD} - 1.0$ V</td>
<td></td>
</tr>
<tr>
<td>Input offset voltage</td>
<td>$T_A = 25^\circ$C, Typ = 5 $\mu$V</td>
<td>Satisfies the offset voltage specification required for the op-amp.</td>
</tr>
<tr>
<td></td>
<td>Max. 500 $\mu$V over the entire temperature range</td>
<td></td>
</tr>
</tbody>
</table>

Note: For the detailed specifications of LMR1802G-LB, refer to the data sheet.

Table 4. Summary of the LMR1802G-LB op-amp and result of examination

The required input offset voltage range is ensured over the entire temperature range. Op-amp LMR1802G-LB was selected because of: small temperature drift of the offset voltage (0.4 $\mu$V/°C). In power applications, heat may be generated not only by the shunt resistor but also by peripheral circuits (for example, by a switching transistor). Therefore, it can be anticipated that the surrounding temperature environment is undesirable. In addition, if the gain setting is relatively high, the input referred noise voltage also emerges as an error. LMR1802G-LB has achieved an industry-leading low noise with excellent usability.
### Notes

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