1. Introduction

The recent rise in awareness of environmental issues and the corresponding demand for energy savings has seen an increase in the use of inverter technology in a wide range of fields, including industrial machinery, power equipment, and home appliances. The demand for industrial inverters such as general-purpose inverters and AC servos is growing strongly in the traditional European and North American markets and is also taking off in emerging markets. Demand for inverter technology is also expected to grow in the expanding “clean energy” fields of solar and wind power generation. One of the most common semiconductor devices used in these inverters is an IGBT (Insulated Gate Bipolar Transistor).

This application note describes the features and applications of PS9505/PS9305 as an example to describe its characteristics, its internal gate driving circuit and describe the external gate resistance requirement and the details of gate driver photocoupler power dissipation in relation to MOSFET / IGBT gate charge based on desired switching frequency to turn-on and turn-off the MOSFET / IGBT.

<table>
<thead>
<tr>
<th>Table 1-1. Specification Outline of PS9505/PS9305</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part No.</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>PS9505</td>
</tr>
<tr>
<td>PS9305</td>
</tr>
</tbody>
</table>

Note: 1. Built-in UVLO function

2. Product overview

Figure 2-1 shows the equivalent circuit of the PS9505/PS9305. The PS9505 is an 8-pin DIP and the PS9305 is an 8-pin SDIP high-speed photocoupler. These contain a GaAlAs light emitting diode (LED) on the input side and photo detector IC that integrates a photodiode (PD), signal processing circuit, large-current circuit and UVLO is configured on the side that outputs signals to the IGBT. The photo detector IC is fabricated with the Bi-CMOS process proven in other Renesas Electronics IGBT-driving photocouplers, enabling both a high output current (I_O = 2.5 A MAX.) and low circuit current (I_C = 2 mA TYP.), which enables high-temperature operation (T_A = 110°C MAX.).
3. UVLO (Under Voltage Lock Out) FUNCTION

The UVLO circuit holds $V_O$ at low level when the PS9505/PS9305 power supply voltage is insufficient. If the IGBT’s gate voltage ($V_O$ in the PS9505/PS9305) drops during on state, the $V_{CE}$ (sat) of the IGBT becomes larger and it might cause a large amount of power to dissipate, leading to overheating and failure of the IGBT. To prevent this, if the PS9505/PS9305 detects that its power supply voltage ($V_{CC2} - V_E$) is insufficient, it holds $V_O$ at low level to protect the IGBT.

As shown in Figure 3-1, when the PS9505/PS9305 power supply voltage ($V_{CC2} - V_E$) is low (when the power supply voltage is rising from 0 V), the PS9505/PS9305 holds the $V_O$ output at low level until the voltage rises to $V_{UVLO+}$, even if the LED is on. Conversely, when the PS9505/PS9305 power supply voltage ($V_{CC2} - V_E$) is falling (changing to a negative voltage) the $V_O$ output is high level until the voltage reaches $V_{UVLO-}$, but if the voltage falls below $V_{UVLO-}$, the PS9505/PS9305 pulls the $V_O$ output down to low level even if the LED is on.

Therefore, if the PS9505/PS9305 power supply voltage ($V_{CC2} - V_E$) falls below $V_{UVLO-}$ (9.5 to 12.5 V) due to some error, the $V_O$ output of the PS9505/PS9305 will go low even if the LED is on. When the power supply voltage ($V_{CC2} - V_E$) subsequently rises to above $V_{UVLO+}$ (10.8 to 13.4 V), the $V_O$ output goes high again (with the LED on).

4. DESIGN OF IGBT GATE DRIVE CIRCUIT

Figure 4-1 shows an example of an IGBT drive circuit using the PS9505. The gate resistance settings described in sections 4.1 and 4.2 are implemented. PS9305 can be used with same circuit to change pin 6 to $V_EE$, pin 1 to LEDH and pin 2 to LEDL.

4.1. Calculation of Minimum Value of IGBT external Gate Resistance $RG$

(1) Calculation from the photocoupler side

The external gate resistor ($RG$) must be selected so that the peak output current of the PS9505/PS9305 ($I_{OL(Peak)}$) does not exceed its maximum rating. The minimum value of the gate resistor ($RG$) can be approximated by using the following expression:

$$RG \geq \frac{(V_{CC2} - V_{EE}) - V_{OL}}{I_{OL(Peak)}} \cdots (4.1)$$

$V_{CC2} - V_{EE}$: PS9505/PS9305 power supply difference ($V_{EE} = 0$ when not using a negative power supply)

$V_{OL}$: PS9505/PS9305 low-level output voltage. Calculate the minimum value of the external gate resistor ($RG$) under the following conditions:

$I_{OL(Peak)} = 2.5 \text{ A}$

$V_{CC2} - V_{EE} = 20 \text{ V}$

Voltage drops to $V_{OL} = 3.5 \text{ V}$ at $T_A = -40 \degree \text{C}$ (as a worst case) while $I_{OL} = 2.5 \text{ A}$. Characteristics curves showing the relationship between the low-level output voltage ($V_{OL}$) and low-level
output current ($I_{OL}$) are provided in Figure 4.2 for reference. These settings make allowances for operation under low temperatures (–40°C).

Note that because the low-side MOSFET voltage drops more than the high-side MOSFET voltage in the PS9505/PS9305, the minimum value of the external gate resistor ($R_G$) is calculated based on the low-side MOSFET. From equation (4.1):

$$R_G \geq \frac{(V_{CC2} - V_{EE}) - V_{OL}}{I_{OL(PEAK)}} = \frac{(20 - 3.5)}{2.5} = 6.6 \, \Omega$$

Because a constant driving voltage $V(DR)$ is used, the relationship between the gate peak current and the total gate resistance ($R_g$) is as follows:

$$R_g = \frac{V(DR)}{I_G},$$

with $R_g$ indicating the sum of the driver’s output impedance, the external gate resistance, and the gate’s own series resistance.

Therefore, in order to satisfy the switching time required by the system, the external gate resistance calculated from the photocoupler side ($R_G$) must be smaller than the total gate resistance calculated from the IGBT side ($R_g$). If $R_g$ is unable to be satisfied, you will have to consider selecting a photocoupler that can drive a larger current, or attaching an external current amplifier (buffer).

### 4.2 Checking the allowable dissipation of the PS9505/PS9305 and adjusting $R_G$

The power consumption of the PS9505/PS9305 ($P_T$) is a total of the power consumption of the LED on the input side (primary side) ($P_D$) and the power consumption of the photo detector IC on the output side (secondary side) connected to the IGBT ($P_O$).

$$P_T = P_D + P_O \quad \ldots (4.2.1)$$

#### (1) LED power consumption

The power consumption of the LED on the input side (primary side) ($P_D$) is calculated as follows:

$$P_D = I_F \times V_F \times \text{Duty ratio} \quad \ldots (4.2.2)$$

#### (2) Photo detector IC power consumption

The power consumption of the photo detector IC on the output side (secondary side) ($P_O$) is calculated as follows:

$$P_O = P_{O(Circuit)} + P_{O(Switching)} \quad \ldots (4.2.3)$$

$P_{O(Circuit)}$ is the circuit power consumption of the photo detector IC (the power consumed by $I_{CC2}$).

$P_{O(Switching)}$ is the power consumption of the photo detector IC required to charge and discharge the gate capacitor (the power consumed by $I_o$).

1. **Circuit power consumption of photo detector IC:**

   $$P_{O(Circuit)} = I_{CC2} \times (V_{CC2} - V_{EE}) \quad \ldots (4.2.4)$$

   $I_{CC2}$ is the circuit current supplied to the photo detector IC.

   $V_{CC2} - V_{EE}$ is the power supply difference of the photo detector IC.

2. **Power consumption of photo detector IC required to charge and discharge the IGBT gate capacitor**

   $$P_{O(Switching)} = E_{sw}(R_G, Q_G) \times f_{sw} \quad \ldots (4.2.5)$$

   $E_{sw}(R_G, Q_G)$ is the per-cycle power consumed when charging the IGBT gate capacitor (see Figure 4.4 and Figure 4.5). $f_{sw}$ is the switching frequency.
3. Power consumption of photo detector IC
From the calculations in (4.2.3), (4.2.4) and (4.2.5), the power consumption of the photo detector IC is as follows:

\[
P_{O} = P_{O\text{(Circuit)}} + P_{O\text{(Switching)}}
\]

\[
= I_{CC2} x (V_{CC2} - V_{EE}) + Esw(RG, Q_g) x f_{sw} \cdots (4.2.6)
\]

5. PS9505/PS9305 PERIPHERAL CIRCUIT

5.1 Layout
1. To minimize floating capacitance between the primary side and the secondary side (the input and the output), be sure to place the circuits so that they are not too close to the primary-side and secondary-side wiring patterns on the board, and that there is no cross-wiring if multi-layer wiring is being used.
2. To prevent transient noise from the IGBT from affecting the PS9505/PS9305, keep the IGBT collector/emitter circuit pattern and DC lines (P and N lines) of the inverter circuit through which a large current flows as far away as possible from the PS9505/PS9305 LED driver and V_{CC2} and V_{O} lines.
3. Design the layout of the bypass capacitor (0.1 μF or higher) between V_{CC} – V_{EE} on the secondary side (output side) of the PS9505/PS9305 so as to be as close as possible to the V_{CC} (pin 8) and V_{EE} (pin 5) of the PS9505/PS9305 (so that the PS9505/PS9305 pins and capacitor pins are as close as possible).
5.2 LED driver
Design the LED driver so that the recommended current \((I_F)\) and voltage \((V_F)\) are applied to the LED. Table 5-1 shows the recommended operating conditions for the LED.

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>MIN.</th>
<th>TYP.</th>
<th>MAX.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage (OFF)</td>
<td>(V_r) (OFF)</td>
<td>-2</td>
<td>0.8</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Input current (ON)</td>
<td>(I_r) (ON)</td>
<td>7</td>
<td>10</td>
<td>16</td>
<td>mA</td>
</tr>
</tbody>
</table>

Table 5-1. Recommended Operating Conditions for PS9505/PS9305 LED

To ensure that the LED is turned off properly, even if common mode noise \((C_{LM})\) occurs, we recommend applying a reverse bias to the LED within the range indicated by the recommended operating conditions in Table 5-1. Similarly, to ensure that the LED is turned on properly, even if common mode noise \((C_{MH})\) occurs, we recommend specifying as large a LED current \((I_F)\) as possible, within the range indicated by the recommended operating conditions in Table 5-1.

6. Specifying dead time
As shown in Figure 6.1, in the inverter circuit, IGBT 1 and IGBT 2 on the upper and lower arms alternately switch on and off, outputting a signal to the motor or other load. If there is insufficient dead time, IGBT 1 and IGBT 2 on the upper and lower arms switch on at the same time, causing a short-circuit current to flow, damaging the IGBTs (see Figure 6.2, example of PS9505).

\[
t_{\text{dead}} \geq t_{\text{off total MAX.}} - t_{\text{on total MIN.}} = (t_{\text{PHL \, MAX. \,(PC)}} + t_{\text{off \, MAX. \,(IGBT)}}) - (t_{\text{PLH \, MIN. \,(PC)}} + t_{\text{on \, MIN. \,(IGBT)}}) = \text{PDD \,(PC)} + (t_{\text{off \, MAX.}} - t_{\text{on \, MIN.}}) \,(\text{IGBT})
\]

In the above equation, \((PC)\) is the response time of the PS9505/PS9305 photocoupler and \((IGBT)\) is the response time of the IGBT.

![Figure 6-3. Deadtime (t\text{dead})](image)

In the PS9505/PS9305, the transmission delay time difference between any two parts has been prescribed to make specifying dead time easy (this time is \(\text{PDD} = t_{\text{PHL}} - t_{\text{PLH}} = \pm100\,\text{ns}\) See the PS9505/PS9305 data sheet for details. Note that \(\text{PDD}\) in the PS9505/PS9305 must be measured under the same temperature and measurement conditions as \(t_{\text{PHL}}\) and \(t_{\text{PLH}}\). The board must therefore be laid out so that the ambient conditions of the upper and lower arms of the photocoupler are the same. Also be sure to thoroughly evaluate the dead time using the actual device, and allow a sufficient margin in your design.

7. Calculation of Junction Temperature
1. PS9505/PS9305 thermal resistance model

![Figure 7-1. Thermal Resistance Model of PS9505/PS9305](image)
Figure 7.1 shows the thermal resistance model of the PS9505/PS9305. The model used has two heat sources: the LED and the photo detector IC.

\[
\begin{align*}
T_{JE} & \quad \text{LED junction temperature} \\
T_{JD} & \quad \text{Light receiving IC junction temperature} \\
T_a & \quad \text{Ambient temperature} \\
\theta_1 & \quad \text{Thermal resistance between LED-ambient temperature} \\
\theta_2 & \quad \text{Thermal resistance between LED-light receiving IC} \\
\theta_3 & \quad \text{Thermal resistance between light receiving IC-ambient temperature}
\end{align*}
\]

2. Junction temperature calculation

In the above model, the junction temperature of LED and photo detector IC is calculated as follows:

\[
T_{JE} = R_{11} \times P_E + R_{12} \times P_D + T_a \quad (7.1)
\]

\[
T_{JD} = R_{21} \times P_E + R_{22} \times P_D + T_a \quad (7.2)
\]

- **P** \(_E\) ... Power consumption of LED
- **P** \(_D\) ... Power consumption of light receiving IC
- **R** \(_{11}\) ... LED-ambient temperature thermal resistance parameter \((R_{11} = \theta_1 \parallel (\theta_2 + \theta_3))\)
- **R** \(_{12}\), **R** \(_{21}\) ... LED-light receiving IC thermal resistance parameter \((R_{12}, R_{21} = (\theta_1 \times \theta_3)/(\theta_1 + \theta_2 + \theta_3))\)
- **R** \(_{22}\) ... Light receiving IC-ambient temperature thermal resistance parameter \((R_{22} = \theta_3 \parallel (\theta_1 + \theta_2))\)

### Table 7-1. Thermal Resistance Parameter

<table>
<thead>
<tr>
<th></th>
<th><strong>R</strong> (_{11})</th>
<th><strong>R</strong> (<em>{12}), <strong>R</strong> (</em>{21})</th>
<th><strong>R</strong> (_{22})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PS9505 TYP.</strong></td>
<td>244</td>
<td>136</td>
<td>182</td>
</tr>
<tr>
<td><strong>PS9305 TYP.</strong></td>
<td>293</td>
<td>124</td>
<td>166</td>
</tr>
</tbody>
</table>

The following is an example of PS9505, calculating the junction temperature using (7.1) and (7.2), with \(P_E = 27\, \text{mW}\), \(P_D\) \(=P_0\) = 124 mW, and \(T_a = 85^\circ\text{C}\):

\[
\begin{align*}
T_{JE} & = R_{11} \times P_E + R_{12} \times P_D + T_a \\
& = 244^\circ\text{C}/\text{W} \times 27 \, \text{mW} + 136^\circ\text{C}/\text{W} \times 124 \, \text{mW} + 85^\circ\text{C} \\
& = 108.5^\circ\text{C}
\end{align*}
\]

\[
\begin{align*}
T_{JD} & = R_{21} \times P_E + R_{22} \times P_D + T_A \\
& = 136^\circ\text{C}/\text{W} \times 27 \, \text{mW} + 182^\circ\text{C}/\text{W} \times 124 \, \text{mW} + 85^\circ\text{C} \\
& = 111.2^\circ\text{C}
\end{align*}
\]

Also an example of PS9305, calculating the junction temperature using (7.1) and (7.2), with \(P_E = 27\, \text{mW}\), \(P_D\) \(=P_0\) = 124 mW, and \(T_a = 85^\circ\text{C}\):

\[
\begin{align*}
T_{JE} & = R_{11} \times P_E + R_{12} \times P_D + T_a \\
& = 293^\circ\text{C}/\text{W} \times 27 \, \text{mW} + 124^\circ\text{C}/\text{W} \times 124 \, \text{mW} + 85^\circ\text{C} \\
& = 108.3^\circ\text{C}
\end{align*}
\]

\[
\begin{align*}
T_{JD} & = R_{21} \times P_E + R_{22} \times P_D + T_A \\
& = 124^\circ\text{C}/\text{W} \times 27 \, \text{mW} + 166^\circ\text{C}/\text{W} \times 124 \, \text{mW} + 85^\circ\text{C} \\
& = 108.9^\circ\text{C}
\end{align*}
\]

Set junction temperatures \(T_{JE}\) and \(T_{JD}\) to values lower than \(125^\circ\text{C}\).

8. Summary

This application note describes the features and applications of the PS9505/PS9305 photocoupler, which is an IGBT-driving photocoupler with built-in IGBT protection circuits. Please use this document when designing your system. The PS9505/PS9305 aims to facilitate the design of inverter equipment—a market that is expected to grow significantly in the future and contribute to reducing system scale. In addition to aggressively marketing the PS9505/PS9305, Renesas Electronics also plans to continue developing photocouplers that support high-temperature operation and high-output devices.