MOSFET

# MOSFET Gate Resistor Setting for Motor Driving

## Introduction

This document describes how to determine the gate resistor, when gate current flows into or out of a MOSFET by a constant voltage in motor drive applications. The gate resistors are determined by the electrical characteristics of the MOSFET, the electrical characteristics of the pre-driver or gate driver and the target output switching time.

### Application

All types of motor application with half-bridge topology.  Three phase motor driving, H-bridge motor driving.

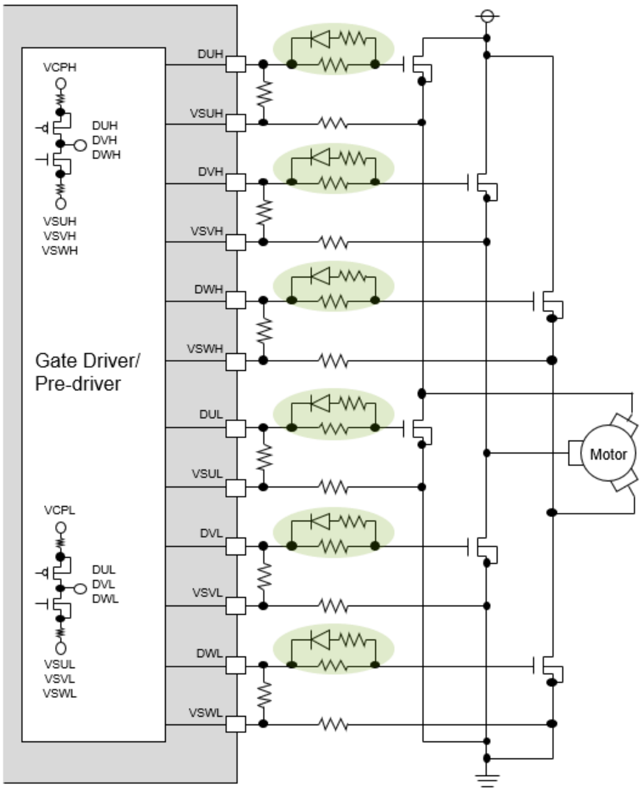


Figure 1. Motor application example:

Gate driver with constant-voltage gate drive for external MOSFET



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## Contents

## Basic MOSFET operation in a half-bridge circuit when driving a motor

### In case the MOSFET flows current into the motor coil by PWM operation

① High side MOSFET Q1 turns on.
Q1 supplies the motor current Io.
The voltage at the output OUT rises to the supply voltage VM-Ron・Io. Q1 continues to supply Io.

②High side MOSFET Q1 turns off. To prevent shoot-through, there is a time to turn off the high side and low side MOSFETs at the same time.
Motor coil tries to keep Io flowing.
OUT voltage falls and the motor current Io continues to flow through the parasitic diode of the low side MOSFET Q2, which is turned off.

③Low side MOSFET Q2 turns on. The motor current Io flows through the turned-on Q2.

④Low side MOSFET Q2 turns off.
To prevent shoot-through, there is a time to turn off the high side and low side MOSFETs at the same time.
Motor current Io continues to flow through the parasitic diode of the low side MOSFET Q2

Operation returns to ①.

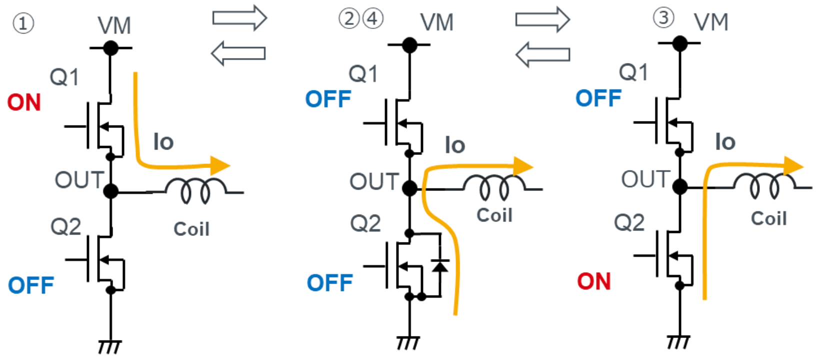


Figure 2. MOS operation of half-bridge circuit for coil drive during current outflow

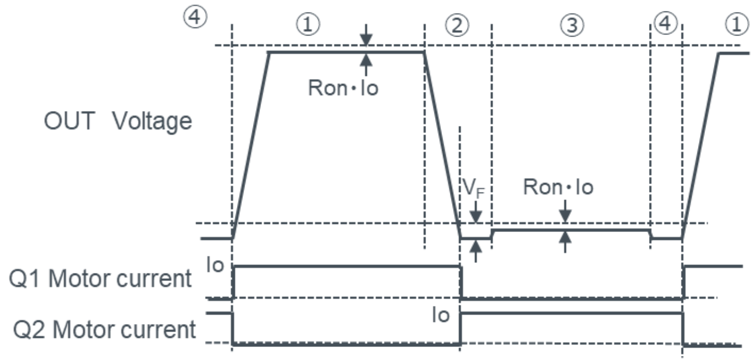


Figure 3. Half-bridge coil drive waveform during current outflow

### In case the MOSFET flows current out of the motor coil by PWM operation

⑤Low side MOSFET Q2 turns on.
Q2 supplies the motor current Io.
The voltage at the output OUT falls to Ron・Io.
Q2 continues to supply Io.

⑥Low side MOSFET Q2 turns off. To prevent shoot-through, there is a time to turn off the high side and low side MOSFETs at the same time.
Motor coil tries to keep Io flowing.
OUT voltage rises and the motor current Io continues to flow through the parasitic diode of the high side MOSFET Q1, which is turned off.

⑦High side MOSFET Q1 turns on. The motor current Io flows through the turned-on Q1.

⑧High side MOSFET Q1 turns off.
To prevent shoot-through, there is a time to turn off the high side and low side MOSFETs at the same time.
Motor current Io continues to flow through the parasitic diode of the high side MOSFET Q1

Operation returns to ⑤.

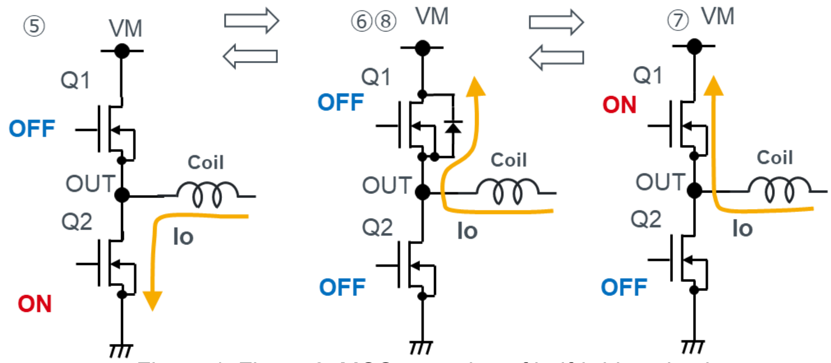


Figure 4. Figure 2. MOS operation of half-bridge circuit for coil drive during current inflow

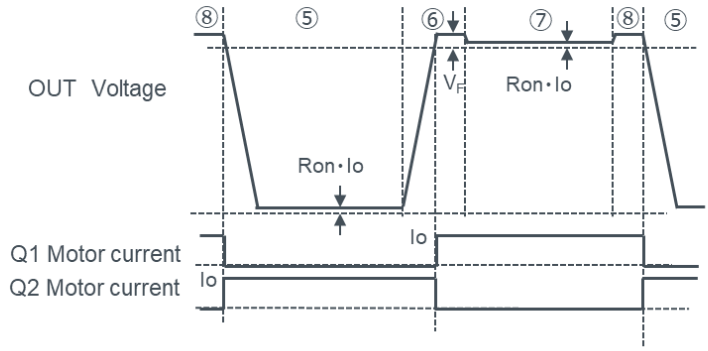


Figure 5. Half-bridge coil drive waveform during current inflow

## Switching time and Transition time definition

Following time range should be decide based on your motor application.

**-$t_{SW}$, $t_{SW\ OFF}$: Switching time from the beginning of Gate voltage to the end of Output voltage transition**

$t_{SW}$ and $t_{SW\ OFF}$ affect to reduce the difference between duty ratio of input PWM from controller and duty ratio of output to the motor, and reduce acoustic noise by reducing the current distortion of three phase motors.

$t_{SW\ OFF}$ should be sufficient shorter than the dead time to prevent shoot-through.

**-$t_{ON}$, $t_{OFF}$: Transition time for output voltage**

$t_{ON}$ and $t_{OFF}$ are equivalent to slew rate of output. Slew rate affect to efficiency and EMC.

**The resistance when the MOSFET turns on is decided by $t_{SW}$ and $t_{ON}$. The resistance when the MOSFET turns off is decided by $t_{SW\ OFF}$ and $t_{OFF}$.**

Figure 6 shows timing chart of half-bridge for motor driving. Motor pre-driver or gate driver outputs gate driving voltage with dead time. Detailed behavior of No.1 to No.35 is as follows:

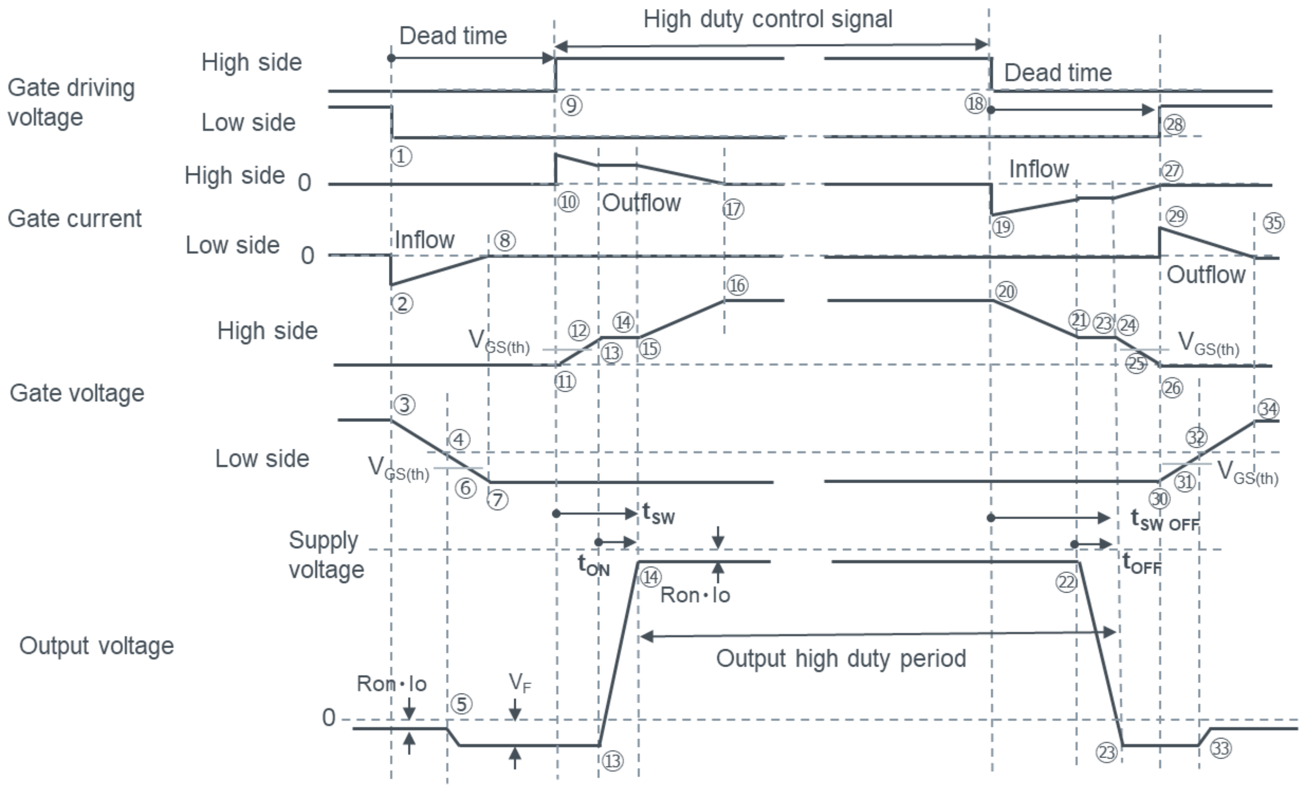


Figure 6. Half-bridge coil drive timing chart [during current outflow]

① Low side gate driving voltage goes to ‘L’
↓
② Driver (Gate driver or pre-driver) draws a current from gate of low side MOSFET through the resistor.
↓
③ Gate voltage of the low side MOSFET decrease from maximum voltage.
↓
④ Gate voltage of the low side MOSFET decrease to stop drain current.
↓
⑤ Output voltage continuously dropped due to low side MOSFET flows motor current with body diode after stop drain current of itself.
↓
⑥ Low side MOSFET turns off by decreasing gate voltage to under $V_{GS(th)}$.
↓
⑦ Gate voltage of the low side MOSFET goes to 0V.
↓
⑧ Gate current of the low side MOSFET to driver decreases to 0A,because gate charge has been to zero.
↓
⑨ High side gate driving voltage goes to ‘H’ after the dead time to prevent shoot through.
↓
⑩ Driver supplies a current to gate of the high side MOSFET through the resistor.
↓
⑪ Gate voltage of high side MOSFET increases.
↓
⑫ High side MOSFET turns on by increasing gate voltage to over $V_{GS(th)}$.
↓
⑬ Output voltage starts to rise, because $V_{GS}$ of high side MOSFET increases to be able to flow current same as path for the body diode of low side MOSFET.
↓
⑭ Output voltage rises to near the supply voltage. During the period, $V_{GS}$ of high side MOSFET is not changed.
↓
⑮ $V_{GS}$ of high side MOSFET increases again after output voltage reaches to near supply voltage.
↓
⑯ Gate Voltage of high side MOSFET reaches to output high voltage of driver.
↓
⑰ Gate current of high side MOSFET is to 0A, because gate charge is full.

⑱ High side gate driving voltage l goes "L”
↓
⑲ Driver draws a current from gate of high side MOSFET through the resistor.
↓
⑳ Gate voltage of the high side MOSFET decrease from maximum voltage.
↓
㉑ $V_{GS}$ of the high side MOSFET decrease to stop drain current.
↓
㉒ Output voltage falls.
↓
㉓ Output voltage go to -Vf due to draw a current from the body diode of low side MOSFET. During the period, $V_{GS}$ of high side MOSFET is not changed.
↓
㉔ After the output voltage goes to -Vf, $V_{GS}$ decreases again.
↓
㉕ High side MOSFET turns off by decreasing gate voltage to under $V_{GS(th)}$.
↓
㉖ Gate voltage of the high side MOSFET goes to 0V.
↓
㉗ Gate current of high side MOSFET is to 0A, because gate charge is empty.
↓
㉘ Low side gate driving voltage to ‘H’ after the dead time to prevent shoot through.
↓
㉙ Driver supplies a current to gate of the low side MOSFET through the resistor.
↓
㉚ Gate voltage of low side MOSFET increases.
↓
㉛ Low side MOSFET turns on by increasing gate voltage to over $V_{GS(th)}$.
↓
㉜ Gate voltage of low side MOSFET increases to be able to flow current same as path for the body diode of low side MOSFET.
↓
㉝ Low side MOSFET flows a current from its body diode had flowed.
↓
㉞ Gate Voltage of low side MOSFET reaches to output high voltage of driver.
↓
㉟ Gate current of low side MOSFET is to 0A, because gate charge is full.

## Gate resistor setting when low side MOSFET is turned on

This parameter affects to the low side Nch MOS-FET is on. The resistor value ($R_{G(LON)}$) when low side MOSFET is turned on can be calculated by deciding either following value on your demand. (See p.4 and Fig. 8,9):

(1) $t_{ON}$: Transition time for output voltage($V_{DS}$)

(2) $t_{SW}$: Switching time from the beginning of $V_{GS}$ to the end of $V_{DS}$ transition.

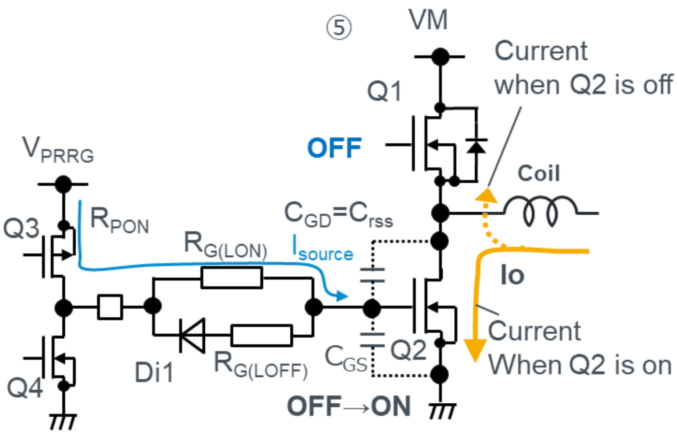


Figure 7. Equivalent circuit at low side on

(1) Calculate the resistor value when low side MOSFET is turned on with $t_{ON}$

Source current $I_{source}$ is calculated by the required electrical charge $Q_{gd}$ and the time $t_{ON}$.

$$I_{source} = \frac{Q_{gd}}{t_{ON}} \qquad (1)$$

$Q_{gd}$ : the required electrical charge from high to low of $V_{DS}$.

Source current $I_{source}$ is calculated by $V_{PRRG}$, $V_{PLT}$, $R_{PON}$ and $R_{G(LON)}$.

$$I_{source} = \frac{(V_{PRRG}-V_{PLT})}{(R_{PON}+R_{G(LON)})} \qquad (2)$$

$V_{PRRG}$ : power supply voltage for gate driver or pre-driver power stage that drives the gate of the low side MOSFET.

$V_{PLT}$ : gate-source constant voltage of low side MOSFET during the time $t_{ON}$.

$R_{PON}$ : Pch MOSFET on resistor of gate driver or pre-driver power stage.

$R_{G(LON)}$ : setting gate resistor.

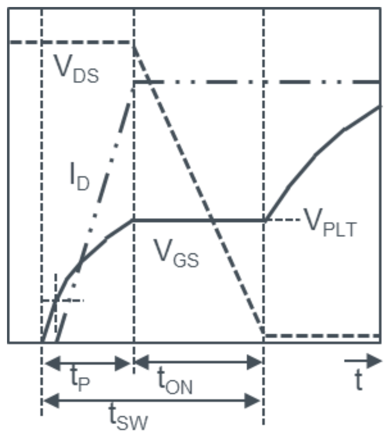


Figure 8. Switching transient waveform

From equations (1) and (2), $R_{G(LON)}$ is:

$$R_{G(LON)} = (V_{PRRG} - V_{PLT}) \times \frac{t_{ON}}{Q_{gd}} - R_{PON} \qquad (3)$$

[Example]

ROHM Nch Dual MOSFET (HPLF5060, $V_{DSS}$=40V, $I_D$=40A)

- Specification (Tentative):

$Q_{gd}$=2.0nC(typ) (conditions: $V_{DD}$≈20V, $I_D$=10A, $V_{GS}$=6V)

$V_{PLT}$=2.1V(typ) (conditions: $V_{DD}$≈20V, $I_D$=10A,$V_{GS}$=10V)

ROHM Three phase motor pre-driver

- Specification (Tentative):

$V_{PRRG}$ =11V(typ)

$R_{PON}$ = 200Ω(typ)

- User Required: (Applicable value for motor application)

$t_{ON}$＝200ns

Required gate resistor is:

$$R_{G(LON)} = (11V - 2.1V) \times \frac{200ns}{2.0nC} - 200\Omega$$

$$= 890\Omega - 200\Omega = 690\Omega \qquad (4)$$

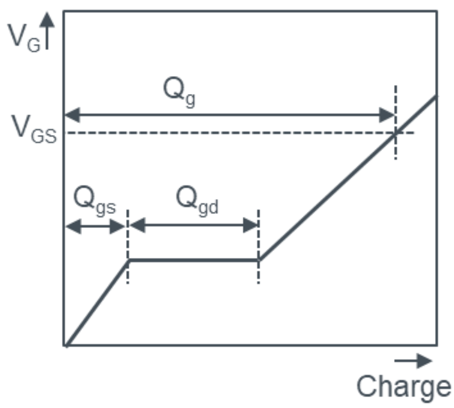


Figure 9. Gate voltage vs. gate charge characteristics

(2) Calculate the resistor value when low side MOSFET is turned on with $t_{SW}$

The input capacitance $C_{iss}$ of the MOSFET is charged by the power supply voltage $V_{PRRG}$ through the series value of resistors $R_{PON}$ and $R_{G(LON)}$. $t_P$ is the time when the gate source voltage ($C_{iss}$ voltage) goes from 0V to the constant voltage $V_{PLT}$ (See Fig. 8). $t_P$ is as follows.

$$t_P = -C_{iss} \times \left(R_{PON} + R_{G(LON)}\right) \times \ln\left(1 - \frac{V_{PLT}}{V_{PRRG}}\right) \quad (5)$$

From equation (3), $t_{ON}$ is as follows.

$$t_{ON} = \left(R_{PON} + R_{G(LON)}\right) \times \frac{Q_{gd}}{(V_{PRRG} - V_{PLT})} \quad (6)$$

$$t_{SW} = t_P + t_{ON} \quad (7)$$

From equation (5), (6) and (7), $R_{G(LON)}$) is as follows.

$$R_{G(LON)} = \frac{t_{SW}}{-C_{iss} \times \ln\left(1 - \frac{V_{PLT}}{V_{PRRG}}\right) + \frac{Q_{gd}}{(V_{PRRG} - V_{PLT})}} - R_{PON} \quad (8)$$

[Example]

ROHM Nch Dual MOSFET (HPLF5060, $V_{DSS}$=40V,$I_D$=40A)
- Specification (Tentative):
  $Q_{gd}$=2.0nC(typ) (conditions: $V_{DD}$ ≈20V, $I_D$=10A, $V_{GS}$=6V)
  $C_{iss}$=630pF(typ) (conditions: $V_{DS}$=12V, $V_{GS}$=0V, f=1MHz)
  $V_{PLT}$=2.1V(typ) (conditions: $V_{DD}$ ≈20V, $I_D$=10A, $V_{GS}$=10V)

ROHM Three phase motor pre-driver
- Specification (Tentative):
  $V_{PRRG}$ =11V(typ)
  $R_{PON}$ = 200Ω(typ)
- User Required: (Applicable value for motor application)
  $t_{SW}$=500ns (1/100 for general PWM frequency 20 kHz)

Required gate resistor is:

$$R_{G(LON)} = \frac{500ns}{-630pF \times \ln\left(1 - \frac{2.1V}{11V}\right) + \frac{2.0nC}{(11V - 2.1V)}} - 200\Omega$$

$$= \frac{500ns}{133pF + 225pF} - 200\Omega$$

$$= 1397\Omega - 200\Omega = 1197\Omega \quad (9)$$

However, since $Q_{gd}$ change with the voltage and current used, correction is necessary in such cases.

## Gate resistor setting when low side MOSFET is turned off

This parameter affects to the low side Nch MOSFET is off. The resistor value ($R_{G(LOFF)}$) when low side MOSFET is turned off can be calculated by deciding either following value on your demand. (See p.4 and Fig.11,12):

(3) $t_{SW\ OFF}$: Switching time from the beginning of $V_{GS}$ to the end of $V_{DS}$ transition.

(4) $t_{OFF}$: Transition time for output voltage

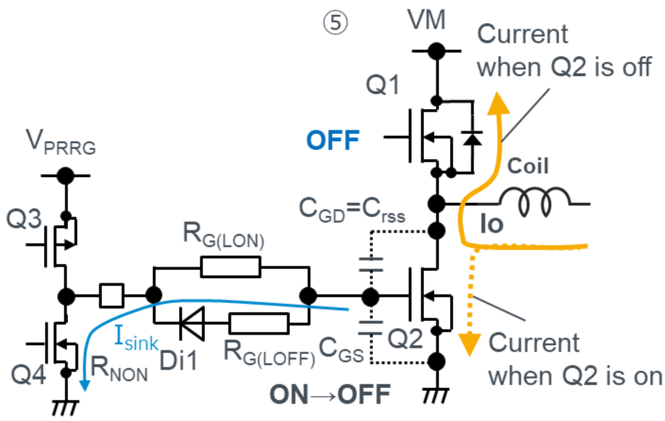


Figure 10. Equivalent circuit at low side off

(3) Calculate the resistor value when low side MOSFET is turned off with $t_{SW\ OFF}$

$t_{PO}$ is the time when the gate source voltage ($C_{iss}$ voltage) goes from gate-source maximum voltage ($V_{PRRG}$) to the constant voltage $V_{PLT}$. The input capacitance $C_{iss}$ of the MOSFET is discharged to GND voltage (0V) through the series value of resistors $R_{NON}$ and $R_{G(LOFF)}$ and diode voltage $V_F$. $t_{PO}$ is as follows.

$$t_{PO} = -C_{iss} \times \left(R_{NON} + R_{G(LOFF)}\right) \times \ln\left(\frac{V_{PLT}}{V_{PRRG} - V_F}\right) \quad (10)$$

$V_{PRRG}$ : power supply voltage for gate driver or pre-driver power stage that drives the gate of the low side MOSFET.

$V_{PLT}$ : gate-source constant voltage of low side MOSFET during the time $t_{OFF}$.

$V_F$ : the forward voltage of the diode.

$R_{NON}$ : Nch MOSFET on resistor of gate driver or pre-driver power stage.

$R_{G(LOFF)}$ : setting gate resistor.

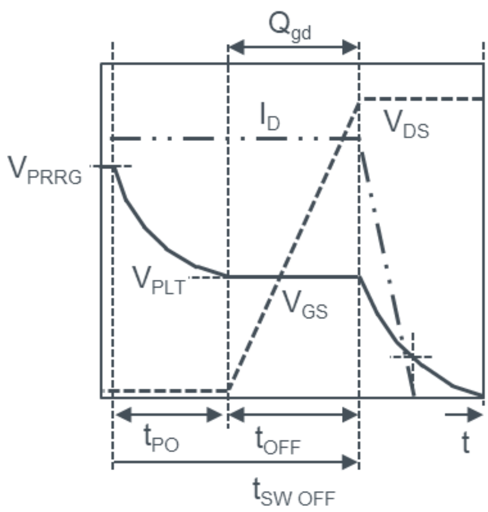


Figure 11. Switching transient waveform

Sink current $I_{sink}$ during $t_{OFF}$ is calculated by the required electrical charge $Q_{gd}$ and the time $t_{OFF}$.

$$I_{sink} = \frac{Q_{gd}}{t_{OFF}} \quad (11)$$

$Q_{gd}$ : the required electrical charge from low to high of $V_{DS}$.

Also, sink current $I_{sink}$ during $t_{OFF}$ is calculated by $V_{PLT}$, $V_F$, $R_{NON}$ and $R_{G(LOFF)}$.

$$I_{sink} = \frac{(V_{PLT} - V_F)}{(R_{NON} + R_{G(LOFF)})} \quad (12)$$

$V_{PLT}$ : gate-source constant voltage of low side MOSFET during the time $t_{OFF}$.

$V_F$ : the forward voltage of the diode.

$R_{NON}$ : Nch MOSFET on resistor of gate driver or pre-driver power stage.

$R_{G(LOFF)}$ : setting gate resistor.

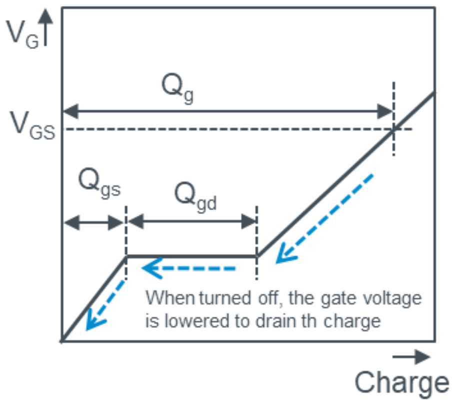


Figure 12. Gate voltage vs. gate charge characteristics

From equation (11) and (12), $t_{OFF}$ is as follows.

$$t_{OFF} = \left(R_{NON} + R_{G(LOFF)}\right) \times \frac{Q_{gd}}{(V_{PLT} - V_F)} \quad (13)$$

$$t_{SW\ OFF} = t_{PO} + t_{OFF} \quad (14)$$

From equation (10), (13) and (14), $R_{G(LOFF)}$ is as follows.

$$R_{G(LOFF)} = \frac{t_{SW}}{-C_{iss} \times \ln\left(\frac{V_{PLT}}{V_{PRRG} - V_F}\right) + \frac{Q_{gd}}{(V_{PLT} - V_F)}} - R_{NON} \quad (15)$$

[Example]

ROHM Nch Dual MOSFET (HPLF5060, $V_{DSS}$=40V,$I_D$=40A)
- Specification (Tentative):
  $Q_{gd}$=2.0nC(typ) (conditions: $V_{DD}$ ≈20V, $I_D$=10A, $V_{GS}$=6V)
  $C_{iss}$=700pF(typ) (conditions: $V_{DS}$ ≈0V, $V_{GS}$=0V, f=1MHz)
  $V_{PLT}$=2.1V(typ) (conditions: $V_{DD}$ ≈20V, $I_D$=10A, $V_{GS}$=10V)

ROHM Three phase motor pre-driver
- Specification (Tentative):
  $V_{PRRG}$ =11V(typ)
  $R_{NON}$ = 150Ω(typ)

ROHM Schottky diode RB160VAM-40
- Specification
  $V_F$=0.26V(typ) (conditions: $I_F$ =50mA, Tj=25°C)
- User Required: (Applicable value for motor application)
  $t_{SW}$=500ns (1/100 for general PWM frequency 20 kHz)

Required gate resistor is:

$$R_{G(LOFF)} = \frac{500ns}{-700pF \times \ln\left(\frac{2.1V}{11V-0.26V}\right) + \frac{2.0nC}{(2.1V-0.26V)}} - 150\Omega$$

$$= \frac{500ns}{1142pF + 1087pF} - 150\Omega$$

$$= 224\Omega - 150\Omega = 74\Omega \qquad (16)$$

(4) Calculate the resistor value when low side MOSFET is turned off with $t_{OFF}$

From equation (13), $R_{G(LOFF)}$ is as follows.

$$R_{G(LOFF)} = \frac{(V_{PLT} - V_F)}{Q_{gd}} \times t_{OFF} - R_{NON} \qquad (17)$$

[Example]

ROHM Nch Dual MOSFET (HPLF5060, $V_{DSS}$=40V,$I_D$=40A)
- Specification (Tentative):
  $Q_{gd}$=2.0nC(typ) (conditions: $V_{DD}$ ≈20V, $I_D$=10A, $V_{GS}$=6V)
  $V_{PLT}$=2.1V(typ) (conditions: $V_{DD}$ ≈20V, $I_D$=10A, $V_{GS}$=10V)

ROHM Three phase motor pre-driver
- Specification (Tentative):
  $R_{NON}$ = 150Ω(typ)

ROHM Schottky diode RB160VAM-40
- Specification
  $V_F$=0.26V(typ) (conditions: $I_F$ =50mA, Tj=25°C)
- User Required: (Applicable value for motor application)
  $t_{ON}$＝200ns

$$R_{G(OFF)} = \frac{(2.1V - 0.26V)}{2.0nC} \times 200ns - 150\Omega$$

$$= 184\Omega - 150\Omega = 34\Omega \qquad (18)$$

**Output voltage transition when turned off does not become steeper than a certain point even if Isink is increased.**

When current is applied to the motor coil by PWM drive, the coil part can be regarded as a constant current load. When Q2 is turned off and the output voltage rises by constant current, the capacitor connected to the Q2 drain is charged to change the voltage.
Output current Io charges $C_{oss}$ of high side and low side MOSFET and output-to-GND capacitor $C_{OUT}$ for noise rejection.
The output voltage transition $dV_{DS}/dt$ is as follows.

$$dV_{DS}/dt = Io/(C_{oss(Q1)} + C_{oss(Q2)} + C_{out}) \quad (19)$$

Output voltage transitions cannot be greater than this, even if sink current increases.

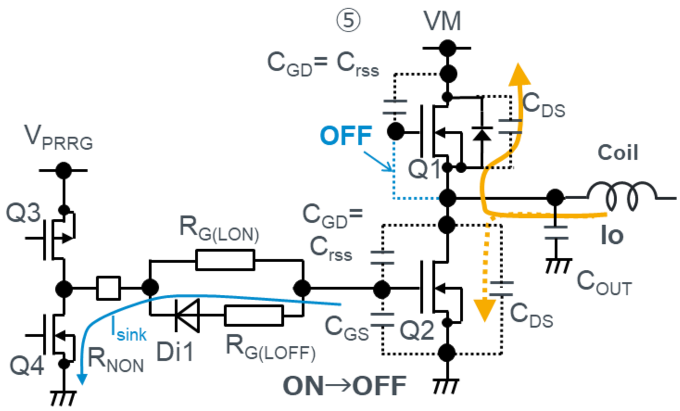


Figure 13. Equivalent circuit 2 at low side off

[Example]

ROHM Nch Dual MOSFET (HPLF5060, $V_{DSS}$=40V, $I_D$=40A)
- Specification (Tentative):
  $C_{oss}$=900pF (conditions: $V_{DS}$=0V, $V_{GS}$=0V, f=1MHz)
  $C_{oss}$=430pF (conditions: $V_{DS}$=12V, $V_{GS}$=0V, f=1MHz)
- Output-to-GND capacitor
  $C_{OUT}$=0nF
- Output current
  Io=5A
- Supply voltage
  VM=12v

Output voltage transition is:

$$dV_{DS}/dt = 5A/(0.90nF + 0.43nF + 0nF) = 3.76V/ns \quad (20)$$

Output transition time is:

$$t_{OFF} = VM/(dV_{DS}/dt) = 12V/3.76V/ns = 3.19ns \quad (21)$$

Output voltage transition when turned off is the later of the value determined by output current and output capacitor or the value determined by gate sink current and $C_{rss}$

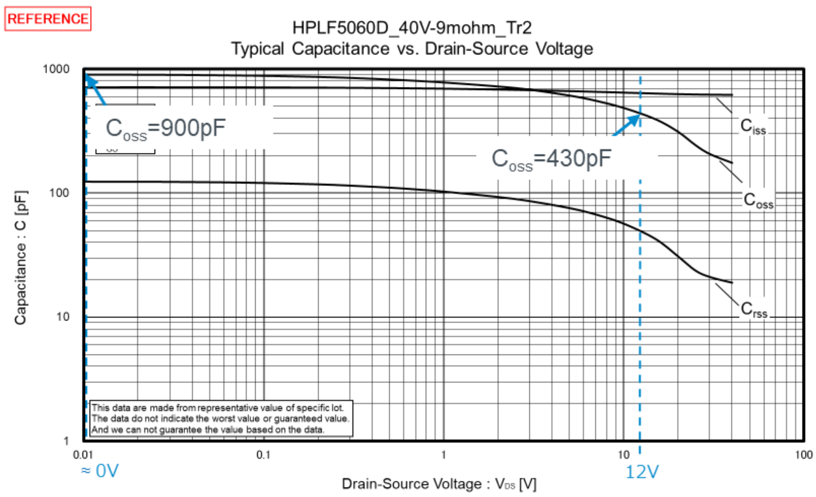


Figure 14. MOSFET Capacitance vs. Drain- Source voltage characteristic

### Gate resistor setting of low side MOSFET drive to prevent self-turn-on

To prevent self-turn-on, changes in drain-source voltage must be such that the current charging the gate-drain capacitor $C_{rss}$ raises the gate-source voltage and does not exceed the gate threshold voltage.

If the change in drain-gate voltage is $d(V_{DS} - V_{GS})/dt$, the current $I_{Crss}$ flowing through $C_{rss}$ is:

$$I_{Crss} = \frac{d(V_{DS}-V_{GS})}{dt} \times C_{rss} = \left(\frac{dV_{DS}}{dt} - \frac{dV_{GS}}{dt}\right) \times C_{rss} \quad (22)$$

If the change in drain-gate voltage is $dV_{GS}/dt$, the current $I_{Cgs}$ flowing through $C_{GS}$ is:

$$I_{Cgs} = \frac{dV_{GS}}{dt} \times C_{GS} \quad (23)$$

If the gate-source voltage is $V_{GS}$, the current $I_{Rgloff}$ through resistor $R_{G(LOFF)}$ is:

$$I_{Rgloff} = \frac{(V_{GS}-V_F)}{(R_{G(LOFF)}+R_{NON})} \quad (24)$$

The relation between $I_{Crss}$, $I_{Cgs}$ and $I_{Rgloff}$ is:

$$I_{Crss} = I_{Cgs} + I_{Rgloff} \quad (25)$$

Substituting equations (22), (23) and (24) into equation (25), we get:

$$(C_{rss} + C_{GS}) \times \frac{dV_{GS}}{dt} + \frac{V_{GS}}{R_{G(LOFF)}+R_{NON}} = \frac{dV_{DS}}{dt} \times C_{rss} + \frac{V_F}{R_{G(LOFF)}+R_{NON}} \quad (26)$$

The right-hand side of equation (26) is a fixed value. From the general solution of the differential equation, $V_{GS}$ is:

$$V_{GS} = \left(R_{G(LOFF)} + R_{NON}\right) \times C_{rss} \times \frac{dV_{DS}}{dt} + V_F \quad +Ae^{-t/\{(C_{rss}+C_{GS})\times(R_{G(LOFF)}+R_{NON})\}} \quad (27)$$

Where the constant A is the initial condition, From $V_{GS}$ = 0V at t = 0s, A is:

$$A = -\left(R_{G(LOFF)} + R_{NON}\right) \times C_{rss} \times \frac{dV_{DS}}{dt} - V_F \quad (28)$$

$$V_{GS} = \left\{\left(R_{G(LOFF)} + R_{NON}\right) \times C_{rss} \times \frac{dV_{DS}}{dt} + V_F\right\} \times \left[1 - e^{-t/\{(C_{rss}+C_{GS})\times(R_{G(LOFF)}+R_{NON})\}}\right] \quad (29)$$

If $V_{GS}$ is less than threshold voltage Vth of Q2, Q2 will not turn on.

$$V_{th} \geq \left\{\left(R_{G(LOFF)} + R_{NON}\right) \times C_{rss} \times \frac{dV_{DS}}{dt} + V_F\right\} \times \left[1 - e^{-t/\{(C_{rss}+C_{GS})\times(R_{G(LOFF)}+R_{NON})\}}\right] \quad (30)$$

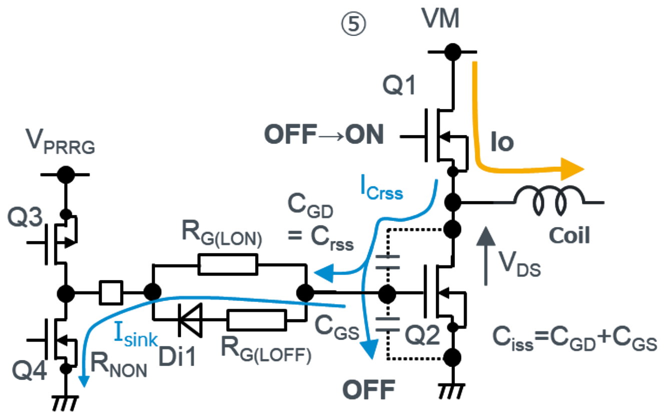


Figure 15. Equivalent circuit at self-turn-on

[Example]

ROHM Nch Dual MOSFET (HPLF5060, $V_{DSS}$=40V,$I_D$=40A)

- Specification (Tentative):
  $C_{iss}$=700pF, $C_{rss}$=120pF (conditions: $V_{DS} \approx$ 0V, $V_{GS}$=0V, f=1MHz)
  $C_{GS} = C_{iss} - C_{rss}$ = 580pF
  $V_{GS(th)}$ =2.0V(min) (conditions: $V_{DS}$=$V_{GS}$、$I_D$=1mA)
  Assuming 0.63V drop at Tj=150°C due to temperature characteristics,
  $V_{GS(th)}$=1.37V(min)

ROHM Schottky diode RB160VAM-40

- Specification
  $V_F$=0.26V(typ) (conditions: $I_F$ =50mA, Tj=25°C)
- The supply voltage
  VM =12V.
- t1 is the time to the point where the tangent line of the steepest point of $V_{DS}$ and the supply voltage intersect in actual operation. Set t1 to 1/2 of $t_{ON}$. (See Fig.16)
  t1=100ns

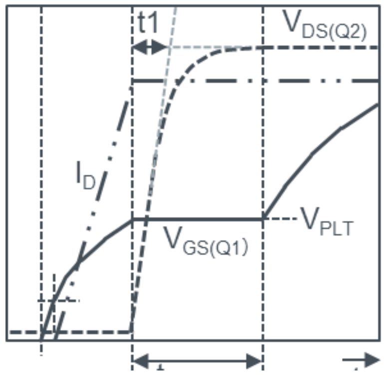


Figure 16. Q2 $V_{DS}$ actual waveform when Q1 is on

Since $R_{G(LOFF)}$+$R_{NON}$ cannot be obtained directly by calculation, we put a number in $R_{G(LOFF)}$+$R_{NON}$ to equation (29) several times, calculate $V_{GS}$. Output $R_{G(LOFF)}$+$R_{NON}$, where $V_{GS}$= $V_{GS(th)}$.

If $R_{G(LOFF)}$+$R_{NON}$ = 117Ω, $V_{GS}$ is:

$$V_{GS} = \left\{117\Omega \times 120p \times \frac{12V}{40ns} + 0.26V\right\} \times \left[1 - e^{-40ns/\{700pF \times 117\Omega\}}\right]$$

$$= 1.94V \times [1 - e^{-1.22}] = 1.94V \times [1 - 0.295] = 1.94V \times 0.705 = 1.37V \qquad (31)$$

Since $V_{GS}$ equal to $V_{GS(th)}$[1.37V(min) (at Tj=150°C)], Self-turn-on does not occur.

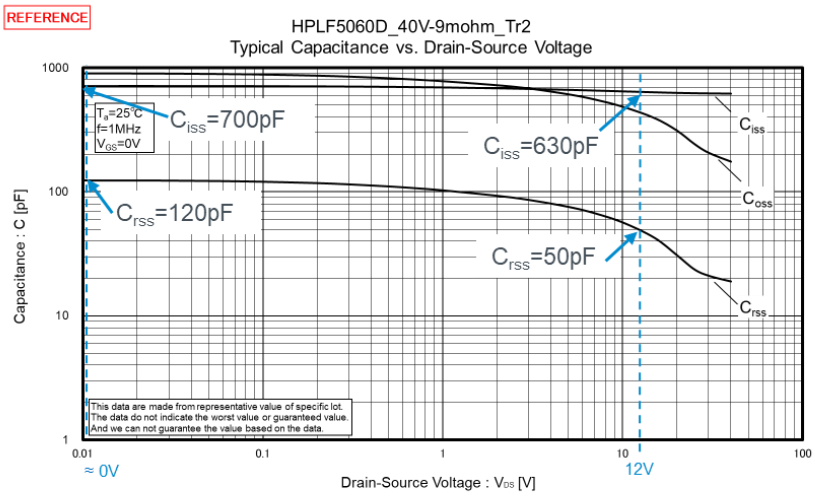


Figure 17. MOSFET capacitance - Drain-source voltage

## Gate resistor setting when high side MOSFET is turned on

When current flows into the gate of the high side Nch MOSFET, the gate voltage rises and reaches $V_{GS}$, which allows the motor current to flow, the source voltage $V_S$ of Q1 rises, and the gate voltage $V_G$ rises with it.
The drain voltage $V_D$ is constant. For this reason, the relative gate-source voltage $V_{GS}$ and the drain-source voltage $V_{DS}$ are similar to the operation of the low side.

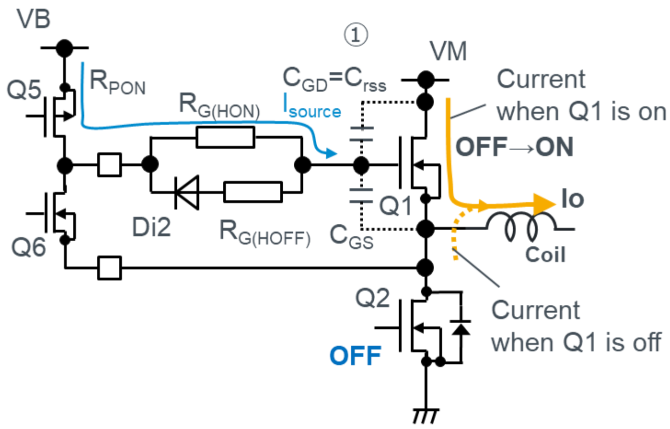


Figure 18. Equivalent circuit at high side on

This parameter affects to the high side Nch MOSFET is on. The resistor value ($R_{G(HON)}$) when high side MOSFET is turned on can be calculated by deciding either following value on your demand. (See p.4 and Fig. 20):

(1) $t_{ON}$: Transition time for output voltage
(2) $t_{SW}$: Switching time from the beginning of $V_{GS}$ to the end of $V_{DS}$ transition.

(1) Calculate the resistor value when high side MOSFET is turned on with $t_{ON}$

(1.1) The boost power supply boosts the voltage when the output voltage rises as in the bootstrap method.

Source current $I_{source}$ is calculated by the required electrical charge $Q_{gd}$ and the time $t_{ON}$.

$$I_{source} = \frac{Q_{gd}}{t_{ON}} \qquad (32)$$

$Q_{gd}$ : the required electrical charge from high to low of $V_{DS}$.

Source current $I_{source}$ is calculated by VB, VM, $V_{PLT}$, $R_{PON}$ and $R_{G(LON)}$.

$$I_{source} = \frac{(VB - VM - V_{PLT})}{(R_{PON} + R_{G(HON)})} \qquad (33)$$

VB : boost power supply voltage for gate driver or pre-driver power stage that drives the gate of the high side MOSFET
VM : power supply voltage for MOSFET
$V_{PLT}$ : gate-source constant voltage of low side MOSFET during the time $t_{ON}$
$R_{PON}$ : Pch MOSFET on resistor of gate driver or pre-driver power stage.
$R_{G(LON)}$ : setting gate resistor.

From equations (32) and (33), $R_{G(HON)}$ is:

$$R_{G(HON)} = (VB - VM - V_{PLT}) \times \frac{t_{ON}}{Q_{gd}} - R_{PON} \qquad (34)$$

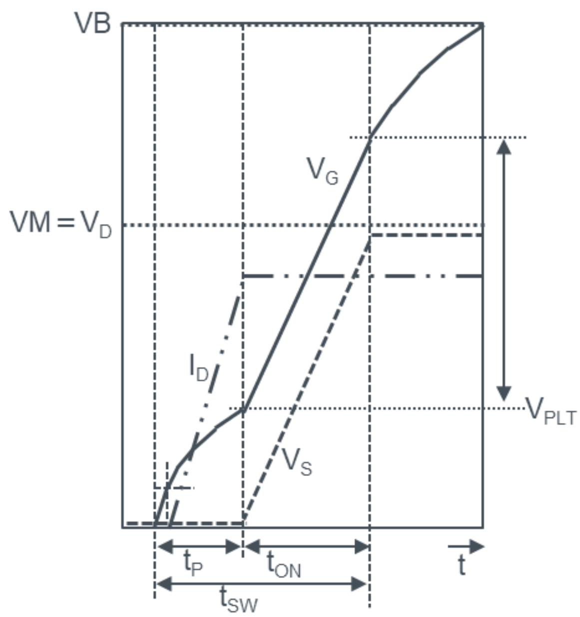


Figure 19. Switching transient waveform (Absolute value)

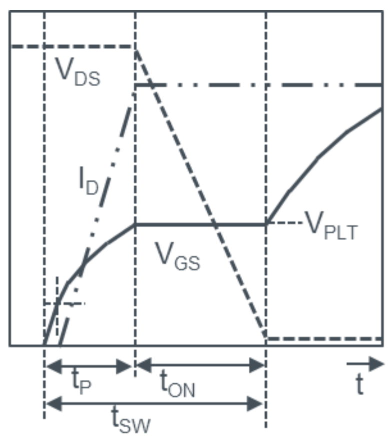


Figure 20. Switching transient waveform (Relative value)

(1.2) The boost power supply boosts the voltage constantly, as in a charge pump method.

Output voltage increases in proportion to time t during $t_{ON}$. The source current transition $I_{source}$ during $t_{ON}$ is as follows.

$$I_{source} = \frac{\left(VB - \frac{VM}{t_{ON}} \times t - V_{PLT}\right)}{(R_{PON}+R_{G(HON)})} \quad (35)$$

The amount of charge Q during $t_{ON}$ is obtained by integrating the current $I_{source}$ between $t_{ON}$. Q is as follows.

$$Q = \frac{\left(VB - \frac{VM}{2} - V_{PLT}\right)\times t_{ON}}{(R_{PON}+R_{G(HON)})} \quad (36)$$

$Q_{gd}$ is determined as the required electrical charge from high to low of $V_{DS}$.

$$Q = Q_{gd} \quad (37)$$

From equation (36) and (37), $R_{G(HON)}$ is:

$$R_{G(HON)} = \frac{\left(VB - \frac{VM}{2} - V_{PLT}\right)\times t_{ON}}{Q_{gd}} - R_{PON} \quad (38)$$

[Example]

ROHM Nch Dual MOSFET (HPLF5060, $V_{DSS}$=40V,$I_D$=40A)

- Specification (Tentative):
  $Q_{gd}$=2.0nC(typ) (conditions: $V_{DD}$≈20V, $I_D$=10A, $V_{GS}$=6V)
  $V_{PLT}$=2.1V(typ) (conditions: $V_{DD}$≈20V, $I_D$=10A,$V_{GS}$=10V)

ROHM Three phase motor pre-driver (Boost power source is charge pump)

- Specification (Tentative):
  VB = VM + 11.5V(typ) (conditions: VM = 11.5 V to 18 V)
  $R_{PON}$ = 200Ω(typ)
-The supply voltage
  VM＝12V
- User Required: (Applicable value for motor application)
  $t_{ON}$＝200ns

Required gate resistor is:

$$R_{G(HON)} = \frac{\left(11.5V+12V - \frac{12V}{2} - 2.1V\right)\times 200ns}{2.0nC} - 200\Omega$$

$$= 1540\Omega - 200\Omega = 1340\Omega \quad (39)$$

(2)Calculate the resistor value when high side MOSFET is turned on with $t_{SW}$

(2.1) The boost power supply boosts the voltage when the output voltage rises as in the bootstrap method.

The input capacitance $C_{iss}$ of the MOSFET is charged by the voltage of boost supply voltage VB minus power supply voltage VM through the series value of resistors $R_{PON}$ and $R_{G(HON)}$.

$t_P$ is the time when the gate source voltage ($C_{iss}$ voltage) goes from 0V to the constant voltage $V_{PLT}$.

$t_P$ is as follows.

$$t_P = -C_{iss} \times \left(R_{PON} + R_{G(HON)}\right) \times \ln\left(1 - \frac{V_{PLT}}{VB-VM}\right) \quad (40)$$

From equation (34), $t_{ON}$ is as follows.

$$t_{ON} = \left(R_{PON} + R_{G(HON)}\right) \times \frac{Q_{gd}}{(VB-VM-V_{PLT})} \quad (41)$$

$$t_{SW} = t_P + t_{ON} \quad (42)$$

From equation (40), (41) and (42), $R_{G(HON)}$) is as follows.

$$R_{G(HON)} = \frac{t_{SW}}{-C_{iss}\times\ln\left(1-\frac{V_{PLT}}{VB-VM}\right)+\frac{Q_{gd}}{(VB-VM-V_{PLT})}} - R_{PON} \quad (43)$$

(2.2) The boost power supply boosts the voltage constantly, as in a charge pump method.

The input capacitance $C_{iss}$ of the MOSFET is charged by boost supply voltage VB through the series value of resistors $R_{PON}$ and $R_{G(HON)}$.

$t_P$ is the time when the gate source voltage ($C_{iss}$ voltage) goes from 0V to the constant voltage $V_{PLT}$.

$t_P$ is as follows.

$$t_P = -C_{iss} \times \left(R_{PON} + R_{G(NON)}\right) \times \ln\left(1 - \frac{V_{PLT}}{VB}\right) \quad (44)$$

From equation (38), $t_{ON}$ is as follows.

$$t_{ON} = \left(R_{PON} + R_{G(LON)}\right) \times \frac{Q_{gd}}{\left(VB - \frac{VM}{2} - V_{PLT}\right)} \quad (45)$$

$$t_{SW} = t_P + t_{ON} \quad (46)$$

From equation (44), (45) and (46), $R_{G(HON)}$) is as follows.

$$R_{G(HON)} = \frac{t_{SW}}{-C_{iss} \times \ln\left(1 - \frac{V_{PLT}}{VB}\right) + \frac{Q_{gd}}{\left(VB - \frac{VM}{2} - V_{PLT}\right)}} - R_{PON} \quad (47)$$

[Example]

ROHM Nch Dual MOSFET (HPLF5060, $V_{DSS}$=40V,$I_D$=40A)

- Specification (Tentative):
  $Q_{gd}$=2.0nC(typ) (conditions: $V_{DD}$≈20V, $I_D$=10A, $V_{GS}$=6V)
  $C_{iss}$=630pF(typ) (conditions: $V_{DS}$=12V, $V_{GS}$=0V,f=1MHz)(
  $V_{PLT}$=2.1V(typ) (conditions: $V_{DD}$≈20V, $I_D$=10A,$V_{GS}$=10V)

ROHM Three phase motor pre-driver (Boost power source is charge pump)

- Specification (Tentative):
  VB = VM + 11.5V(typ) (conditions: VM = 11.5 V to 18 V)
  $R_{PON}$ = 200Ω(typ)
- The supply voltage
  VM = 12V.
- User Required: (Applicable value for motor application)
  $t_{ON}$ = 200ns

Required gate resistor is:

$$R_{G(HON)} = \frac{500ns}{-630pF \times \ln\left(1 - \frac{2.1V}{23.5V}\right) + \frac{2.0nC}{\left(23.5V - \frac{12V}{2} - 2.1V\right)}} - 200\Omega$$

$$= \frac{500ns}{59pF + 130pF} - 200\Omega = 2646\Omega - 200\Omega = 2446\Omega \quad (48)$$

However, since Qgd change with the voltage and current used, correction is necessary in such cases.

## Gate resistor setting when high side MOSFET is turned off

The operation from full on to off is the same as the operation of the low side MOS-FET.
This parameter affects to the high side Nch MOSFET is off.
The resister value ($R_{G(HOFF)}$) when high side MOSFET is turned off can be calculated by deciding either following value on your demand. (See p.4 and Fig.23):

(3) $t_{SW\ OFF}$: Switching time from the beginning of $V_{GS}$ to the end of $V_{DS}$ transition.

(4) $t_{OFF}$: Transition time for output voltage

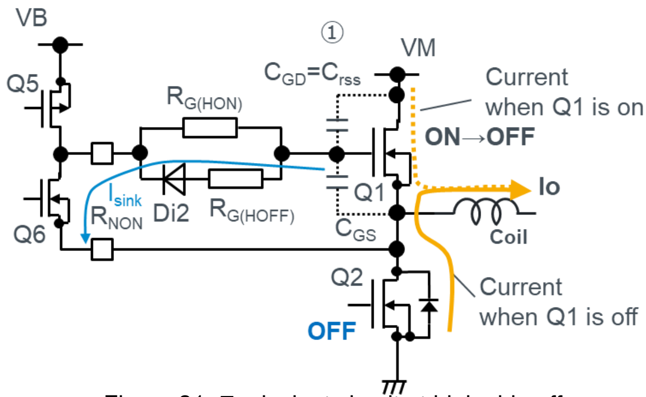

Figure 21. Equivalent circuit at high side off

(3) Calculate the resistor value when high side MOSFET is turned off with $t_{SW\ OFF}$

$t_{PO}$ is the time when the gate source voltage ($C_{iss}$ voltage) goes from gate-source maximum voltage (VB-VM) to the constant voltage $V_{PLT}$.
The input capacitance $C_{iss}$ of the MOS is discharged to GND Voltage (0V) through the series value of resistors $R_{NON}$ and $R_{G(HOFF)}$ and diode voltage $V_F$.
$t_{PO}$ is as follows.

$$t_{PO} = -C_{iss} \times \left(R_{NON} + R_{G(HOFF)}\right) \times \ln\left(\frac{V_{PLT}}{VB - VM - V_F}\right) \quad (49)$$

VB : boost power supply voltage for gate driver or pre-driver power stage that drives the gate of the high side MOSFET.
VM : power supply voltage for MOSFET
$V_{PLT}$ : gate-source constant voltage of high side MOSFET during the time $t_{OFF}$.
$R_{NON}$ : Nch MOSFET on resistor of gate driver or pre-driver power stage.
$R_{G(LOFF)}$ : setting gate resistor

Sink current $I_{sink}$ during $t_{OFF}$ is calculated by the required electrical charge $Q_{gd}$ and the time $t_{OFF}$.

$$I_{sink} = \frac{Q_{gd}}{t_{OFF}} \quad (50)$$

$Q_{gd}$ : the required electrical charge from low to high of $V_{DS}$.

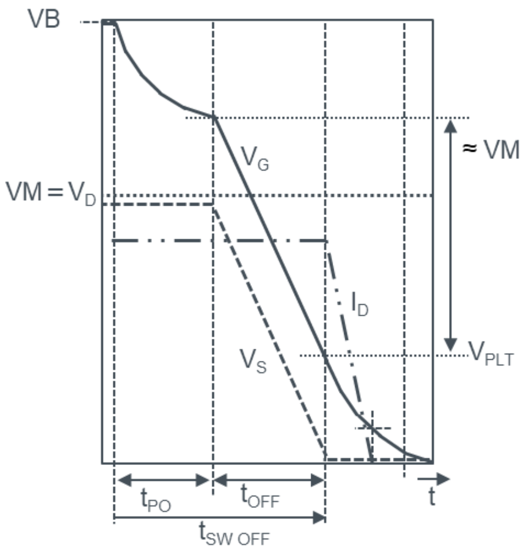

Figure 22. Switching transient waveform (Absolute value)

Also, sink current $I_{sink}$ during $t_{OFF}$ is calculated by $V_{PLT}$, $V_F$, $R_{NON}$ and $R_{G(LOFF)}$.

$$I_{sink} = \frac{(V_{PLT} - V_F)}{(R_{NON} + R_{G(HOFF)})} \quad (51)$$

$V_{PLT}$ : gate-source constant voltage of high side MOSFET during the time $t_{OFF}$.
$V_F$ : the forward voltage of the diode.
$R_{NON}$ : Nch MOSFET on resistor of gate driver or pre-driver power stage.
$R_{G(LON)}$ : setting gate resistor.

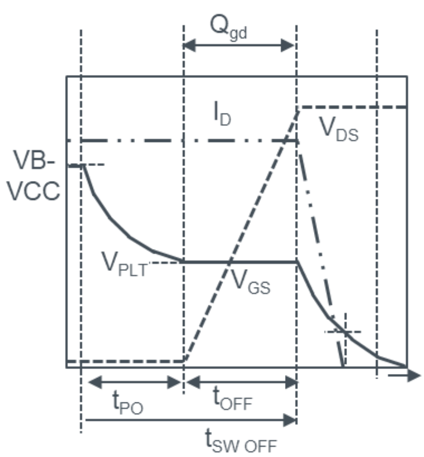

Figure 23. Switching transient waveform (Relative value)

From equation (50) and (51), $t_{OFF}$ is as follows.

$$t_{OFF} = \left(R_{NON} + R_{G(HOFF)}\right) \times \frac{Q_{gd}}{(V_{PLT} - V_F)} \quad (52)$$

$$t_{SW\ OFF} = t_{PO} + t_{OFF} \quad (53)$$

From equation (49), (52) and (53), $R_{G(HOFF)}$ is as follows.

$$R_{G(HOFF)} = \frac{t_{SW}}{-C_{iss} \times \ln\left(\frac{V_{PLT}}{VB - V_{CC} - V_F}\right) + \frac{Q_{gd}}{(V_{PLT} - V_F)}} - R_{NON} \quad (54)$$

[Example]

ROHM Nch Dual MOSFET (HPLF5060, $V_{DSS}$=40V,$I_D$=40A)

- Specification (Tentative):
  $Q_{gd}$=2.0nC(typ) (conditions: $V_{DD}$ ≈20V, $I_D$=10A, $V_{GS}$=6V)
  $C_{iss}$=700pF(typ) (conditions: $V_{DS}$ ≈0V, $V_{GS}$=0V, f=1MHz)
  $V_{PLT}$=2.1V(typ) (conditions: $V_{DD}$ ≈20V, $I_D$=10A, $V_{GS}$=10V)

ROHM Three phase motor pre-driver (Boost power source is charge pump)

- Specification (Tentative):
  VB = VM + 11.5V(typ) (conditions: VM = 11.5 V to 18 V)
  $R_{NON}$ = 150Ω(typ)

ROHM Schottky diode RB160VAM-40

- Specification
  $V_F$=0.26V(typ) (conditions: $I_F$ =50mA, Tj=25°C)
- The supply voltage
  VM＝$V_{CC}$=12V.
- User Required: (Applicable value for motor application)
  $t_{SW}$=500ns (1/100 for general PWM frequency 20 kHz)

Required gate resistor is:

$$R_{G(HOFF)} = \frac{500ns}{-700pF\times\ln\left(\frac{2.1V}{11.5V-0.26V}\right)+\frac{2.0nC}{(2.1V-0.26V)}} - 150\Omega$$

$$= \frac{500ns}{1174pF+1087pF} - 150\Omega$$

$$= 221\Omega - 150\Omega = 71\Omega \qquad (55)$$

(4) Calculate the resistor value when high side MOSFET is turned off with $t_{OFF}$

From equation (52), $R_{G(HOFF)}$ is as follows.

$$R_{G(LOFF)} = \frac{(V_{PLT}-V_F)}{Q_{gd}} \times t_{OFF} - R_{NON} \qquad (56)$$

[Example]

ROHM Nch Dual MOSFET (HPLF5060, $V_{DSS}$=40V,$I_D$=40A)

- Specification (Tentative):
  $Q_{gd}$=2.0nC(typ) (conditions: $V_{DD}$ ≈20V, $I_D$=10A, $V_{GS}$=6V)
  $V_{PLT}$=2.1V(typ) (conditions: $V_{DD}$ ≈20V, $I_D$=10A, $V_{GS}$=10V)

ROHM Three phase motor pre-driver (Boost power source is charge pump)

- Specification (Tentative):
  $R_{NON}$ = 150Ω(typ)

ROHM Schottky diode RB160VAM-40

- Specification
  $V_F$=0.26V(typ) (conditions: $I_F$ =50mA, Tj=25°C)
- User Required: (Applicable value for motor application)
  $t_{OFF}$＝200ns

$$R_{G(OFF)} = \frac{(2.1V-0.26V)}{2.0nC} \times 200ns - 150\Omega$$

$$= 184\Omega - 150\Omega = 34\Omega \qquad (57)$$

**Sink current setting of high side MOSFET drive to prevent self-turn-on**

Even in the case where the high side MOSFET is turned off, when the low side MOSFET is turned on, the gate voltage of the high side MOSFET falls steeply. Since the drain of the high side MOSFET is constant by the supply voltage VM, current flows through the gate-to-drain capacitor $C_{rss}$. To prevent self-turn-on, the gate-source voltage of high side MOSFET must be prevented from rising above the gate threshold voltage by $C_{rss}$ current. Set the sink current using the same approach as for the low side MOSFET. (See Page 11.)

## Additional external capacitors to adjust transition time

An external capacitor between gate and drain may use for adjusting switching and transition time ($C_{GDEX}$ of Fig.24) . $t_{ON}$ and $t_{OFF}$(Output voltage transient time) of low side MOSFET with external capacitor is as follows.

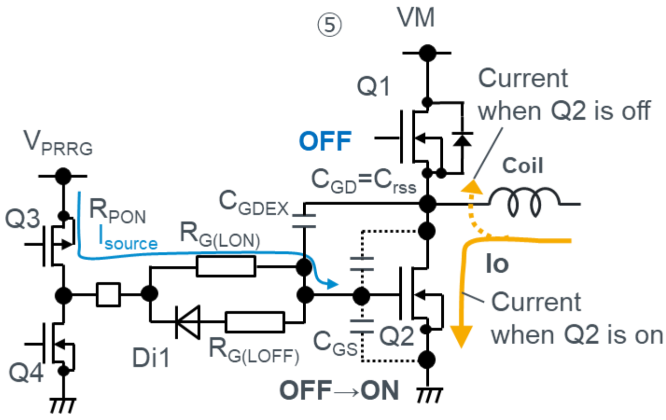


Figure 24. Equivalent circuit with external capacitor added between low side MOSFET gate and drain

(1) Transition time $t_{ON}$ for output voltage when low side MOSFET is turned on

Output voltage transient time $t_{ON}$ is calculated by the VM, $C_{GDEX}$, $Q_{gd}$ and $I_{source}$.

$$t_{ON} = \frac{(VM \times C_{GDEX} + Q_{gd})}{I_{source}} \qquad (58)$$

VM : the transient voltage at the MOSFET drain.
It changes from supply voltage VM to 0V.
$C_{GDEX}$ : the external capacitor between gate and drain.
$Q_{gd}$ : the required electrical charge from high to low of $V_{DS}$.
$I_{souce}$ : source current to the gate.

Source current $I_{source}$ is calculated by $V_{PRRG}$, $V_{PLT}$, $R_{PON}$ and $R_{G(LON)}$.

$$I_{source} = \frac{(V_{PRRG} - V_{PLT})}{(R_{PON} + R_{G(LON)})} \qquad (59)$$

$V_{PRRG}$ : power supply voltage for gate driver or pre-driver power stage that drives the gate of the low side MOSFET.
$V_{PLT}$ : gate-source constant voltage of low side MOSFET during the time $t_{ON}$.
$R_{PON}$ : Pch MOSFET on resistor of gate driver or pre-driver power stage.
$R_{G(LON)}$ : setting gate resistor.

From equation (58) and (59), $t_{ON}$ is:

$$t_{ON} = (VM \times C_{GDEX} + Q_{gd}) \times \frac{(R_{PON} + R_{G(LON)})}{(V_{PRRG} - V_{PLT})} \qquad (60)$$

【Example】

ROHM HPLF5060 Dual Gen.6(Nch MOSFET, $V_{DSS}$=40V, $I_D$=40A)
- Specification (Tentative):
  $Q_{gd}$=2.0nC(typ) (conditions: $V_{DD}$ ≈20V、$I_D$=10A、$V_{GS}$=6V)
  $V_{PLT}$=2.1V(typ) (conditions: $V_{DD}$≈20V、$I_D$=10A、$V_{GS}$=10V)

ROHM Three phase motor pre-driver
- Specification (Tentative):
  $V_{PRRG}$ =11V(typ)
  $R_{PON}$ = 200Ω(typ)

-Supply voltage
  VM=12V

-External capacitor between Gate and Drain
  $C_{GDEX}$=330pF

-Gate resister setting
  (Using previous setting, see page 6)
  $R_{G(LON)}$=690Ω

Output voltage transient time is:

$$t_{ON} = (200\Omega + 690\Omega) \times \frac{(12V \times 330pF + 2.0nC)}{(11V - 2.1V)} = 593ns \qquad (61)$$

$t_{ON}$ is (596ns-200ns =) 396ns slower than the first value.

(2) Transition time $t_{OFF}$ for output voltage when low side MOSFET is turned off

Output voltage transient time $t_{OFF}$ is calculated by the VM, $C_{GDEX}$, $Q_{gd}$ and $I_{sink}$.

$$t_{OFF} = \frac{(VM \times C_{GDEX} + Q_{gd})}{I_{sink}} \quad (62)$$

VM : the transient voltage at the MOSFET drain. It changes from supply voltage VM to 0V.
$C_{GDEX}$ : the external capacitor between gate and drain.
$Q_{gd}$ : the required electrical charge from high to low of $V_{DS}$.
$I_{sink}$ : sink current from the gate.

Sink current $I_{sink}$ during $t_{OFF}$ is calculated by $V_{PLT}$, $V_F$, $R_{NON}$ and $R_{G(LOFF)}$.

$$I_{sink} = \frac{(V_{PLT} - V_F)}{(R_{NON} + R_{G(LOFF)})} \quad (63)$$

$V_{PLT}$ : gate-source constant voltage of low side MOSFET during the time $t_{OFF}$.
$V_F$ : the forward voltage of the diode.
$R_{NON}$ : Nch MOSFET on resistor of gate driver or pre-driver power stage.
$R_{G(LOFF)}$ : setting gate resistor.

From equation (57) and (58), $t_{OFF}$ is:

$$t_{OFF} = (VM \times C_{GDEX} + Q_{gd}) \times \frac{(R_{NON} + R_{G(LOFF)})}{(V_{PLT} - V_F)} \quad (64)$$

【Example】

ROHM HPLF5060 Dual Gen.6(Nch MOSFET, $V_{DSS}$=40V, $I_D$=40A)
- Specification (Tentative):
  $Q_{gd}$=2.0nC(typ) (conditions: $V_{DD}$ ≈20V、$I_D$=10A、$V_{GS}$=6V)
  $V_{PLT}$=2.1V(typ) (conditions: $V_{DD}$≈20V、$I_D$=10A、$V_{GS}$=10V)

ROHM BD63030EVK-C(Pre-driver)
- Specification (Tentative):
  $R_{NON}$ = 150Ω(typ)
-Supply voltage
  VM=12V
-External capacitor between gate and drain
  $C_{GDEX}$=330pF
-Gate resister setting
  (Using previous setting, see page 9)
  $R_{G(LOFF)}$=34Ω

$$t_{OFF} = (12V \times 330pF + 2.0nC) \times \frac{(150\Omega + 34\Omega)}{(2.1V - 0.26V)} = 596ns \quad (65)$$

$t_{ON}$ is (596ns-200ns =) 396ns slower than the first value.

## Notice

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