Relay failures: the solutions, causes and remedies

When MOSFET relays are used under conditions that exceed the absolute maximum ratings even for a moment, it can be disruptive. To ensure the reliability of the MOSFET relay, it is important for the users to carefully consider all environmental conditions – including de-rating design– when using the MOSFET relay. This brochure lists the causes and remedial measures from the past failure events as a guideline to help uncover any unexpected failure causes.

Content

Failure relationship diagrams

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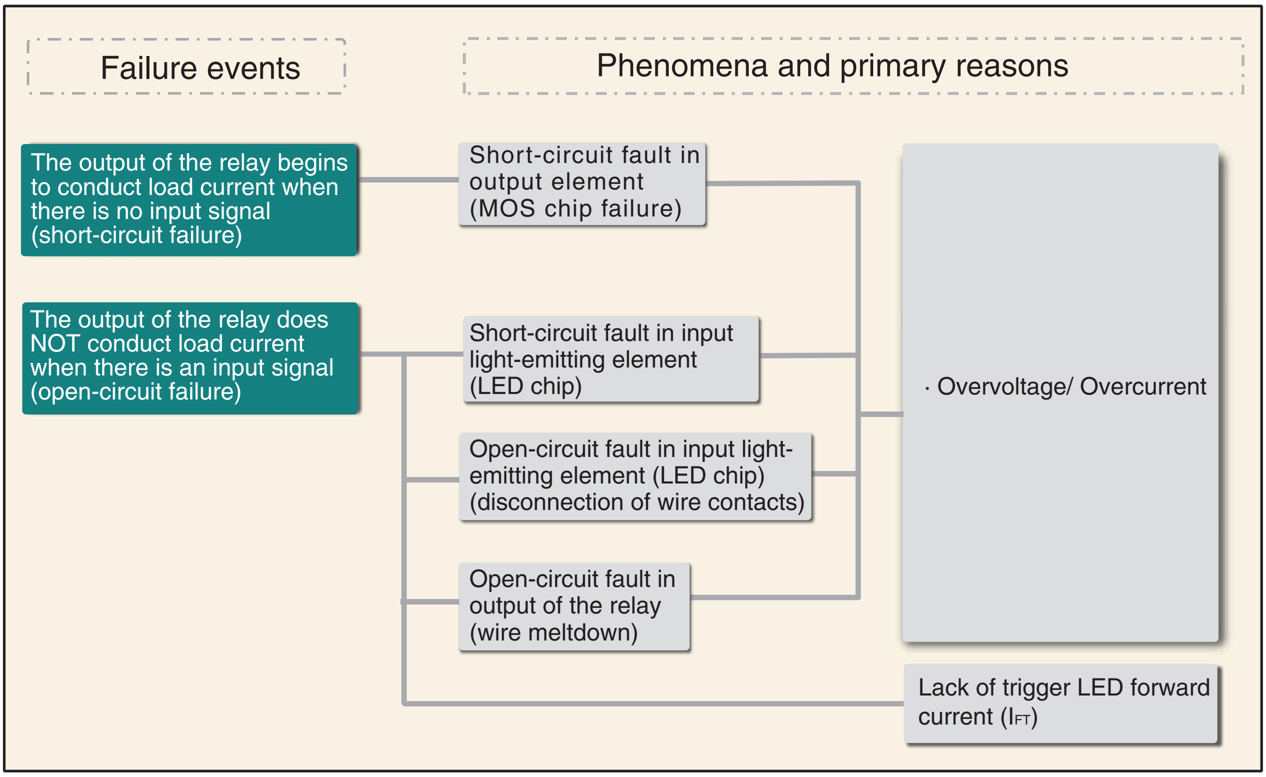
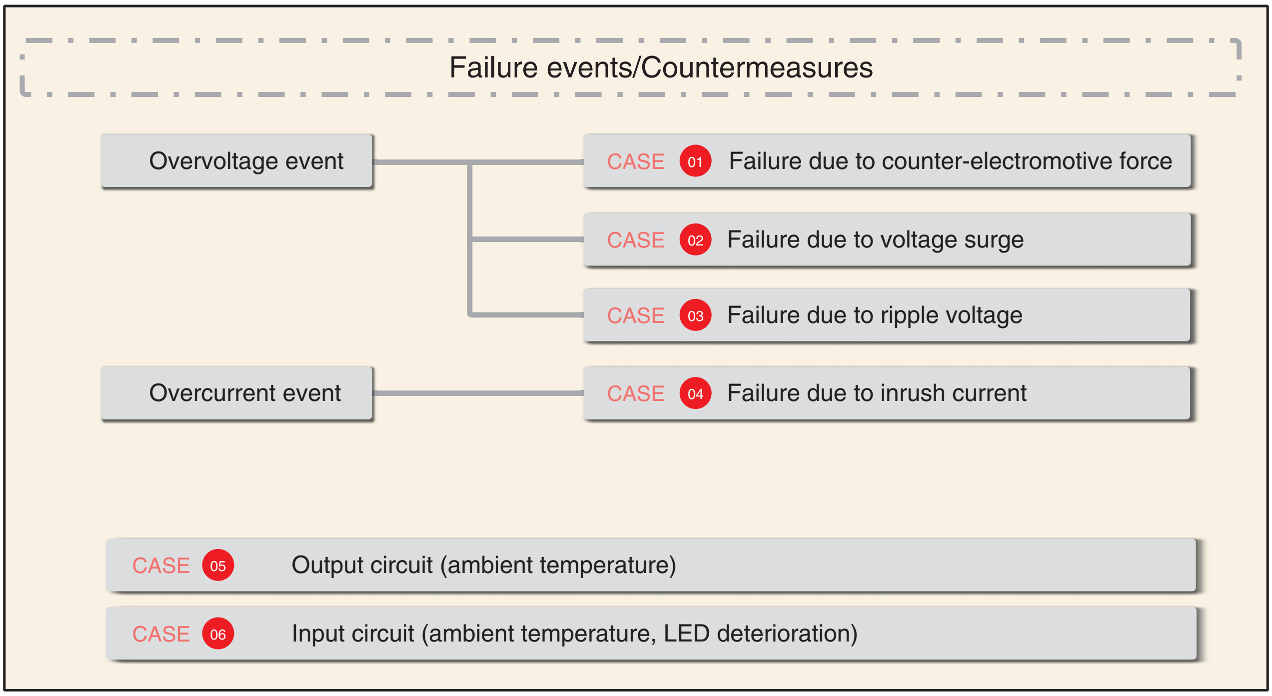
MOSFET relay - Failure Relationship Diagram



MOSFET Relay – Failure Events



COUNTER-ELECTROMOTIVE FORCE

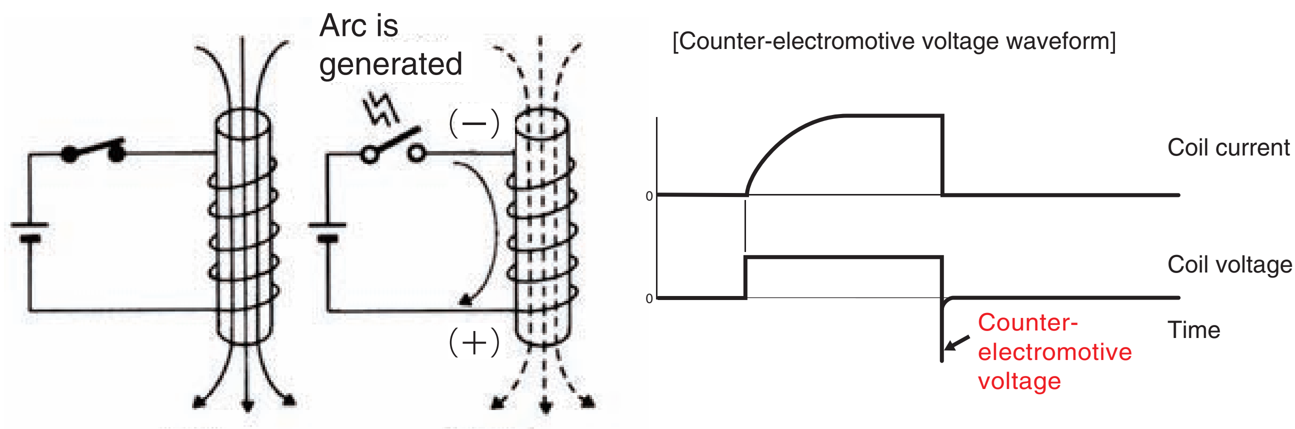
When the counter-electromotive force generated from the interruption of inductive load (L) current (when MOSFET is turned OFF) exceeds the load voltage (V_{OFF}) of the MOSFET, it may cause damage to the output element.

Probable cause of failure

When the switch is turned OFF and power is cut off, the inductive load (L) will try to maintain the flow of the current and generate a voltage in opposite polarity to the voltage applied at both ends of the load. Such voltage is known as counter-electromotive force. When the force exceeds the load voltage (V_{OFF}) of MOSFET, it may damage the output element of MOSFET.

- Short-circuit fault in output element (refer to P15 *Photos of Failure Event*)
  → The output of the relay begins to conduct load current when the LED forward operating current (I_F) is NOT applied across the input terminals (short-mode failure)
- Open-circuit fault in output element (refer to P16 *Photos of Failure Event*)
  → The output of the relay does not conduct load current when the LED forward operating current (I_F) is applied across the input terminals (open-circuit failure)

The coil produces a magnetic flux when voltage is applied (Figure 1).
Once the switch is turned OFF, the magnetic field begins to collapse but the coil's self-induction action opposes this change in the magnetic field by producing a counter-electromotive force (Figure 2).
At this point, the switch is in open circuit preventing the electromotive force arising in the coil from escaping, ultimately producing an extremely high voltage.

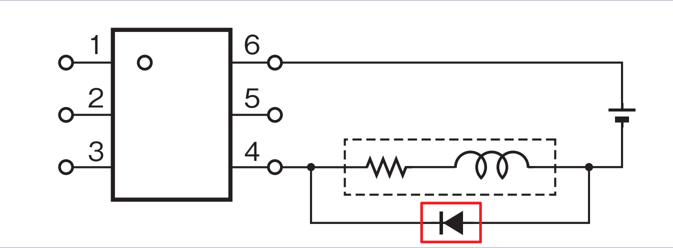


(Figure 1) (Figure 2)

Example) Inductive loads with counter-electromotive force
Solenoid, electromagnetic valve, motor brakes, contactors, and mechanical relay etc.

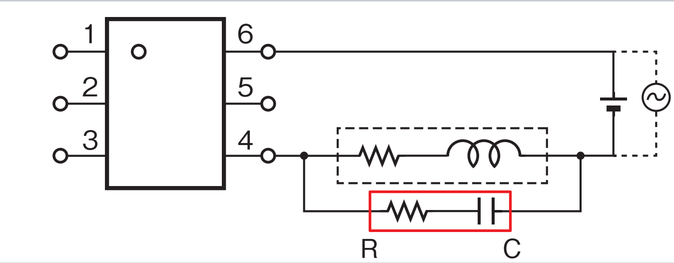
Connect overvoltage protective circuit (protection device) to prevent excess voltage produced in an inductive load.
(To protect from overvoltage exceeding the load voltage (V_{OFF}))

(1) Use external diode to absorb energy



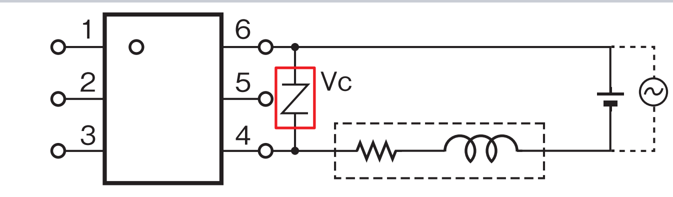
Selection guideline:
The reverse breakdown voltage of the diode must be 10 times higher than the circuit voltage and the forward current as high as or higher than the load current.

(2) Use snubber circuit to absorb energy



Selection guideline:
Indicators for the capacitor and resistor values are as follows:
C: 0.5 to 1 μF for contact current (1 A)
R: 0.5 to 1 Ω for contact voltabe (1 V)
The values may change according to the characteristics of the load.
The capacitor suppresses the spark discharge of current when the contacts are open. The resistor limits the inrush current when the contacts are closed again.
These roles of capacitor and resistor must be considered when determining the ideal capacitance and resistance values by experimentation.
Use a capacitor that can withstand voltage of between 200 and 300 V. For AC circuit, use non-polarized capacitor (a condenser exclusively for AC).
When there is a problem to interrupt the arcs between the contacts at high DC voltage, in some cases, it is more effective in connecting the capacitor and resistor across the contacts rather than across the load. However, a test should be performed on the actual equipment to substantiate this.

(3) Use varistor to reduce overvoltage



Selection guideline:
The cutoff voltage (Vc) of the varistor must satisfy the following conditions. For AC, it must be multiplied by $\sqrt{2}$.
Vc > (supply voltage × 1.5)
If Vc is set too high, the varistor may not be able to reduce high voltage as it should and result to less effect.

Remarks:

- Protection devices may delay the recovery (breaking time) on the load side. Make sure to perform a test under actual load condition to check the performance before actual use.
- Protection devices, including diode, snubber (C-R) and varistor must be installed as close as possible to either the load or MOSFET. Longer distance may affect the performance of the protection device.

VOLTAGE SURGE (INPUT SIDE)

When voltage surge, such as switching surge is applied to the input side of the MOSFET, it may cause damage to the input element.

Probable cause of failure

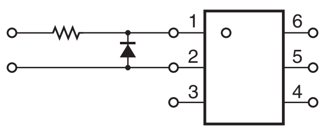
When backward voltage (surge reverse voltage) that exceeds the reverse voltage (V_R) of the LED is applied across the input terminals, it may damage the input light-emitting element (LED chip) ultimately causing malfunction.

- Short-circuit fault in LED chip (refer to P17 *Photos of Failure Event*)
  → The output of the relay does NOT conduct load current (does not turn ON) when LED forward operating current (I_F) is applied across the input terminals.
- Open-circuit fault in LED chip (refer to P17 *Photos of Failure Event*)
  → The output of the relay does NOT conduct load current (does not turn ON) when LED forward operating current (I_F) is applied across the input terminals.
  ＊The substantial drop in light output prevents from switching to ON mode.

COUNTERMEASURE

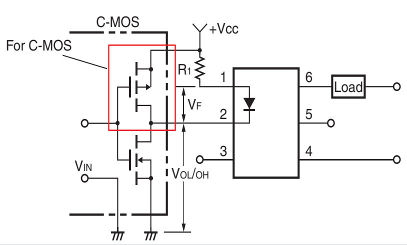
In the event of a backward voltage (surge reverse voltage) applied across the input terminals, place a diode antiparallel to the input terminal to prevent backward voltage that exceeds the reverse breakdown voltage (V_R) of the LED from being applied to the LED chip (Reference: 3 V or less)

Surge protection circuit (input side)

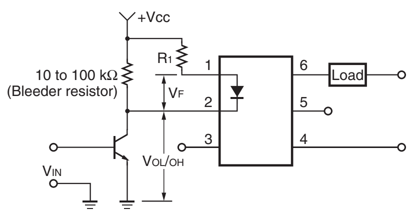


The following circuit is a representative example.

●Representative example of MOSFET relay drive circuit



Transistor



· To ensure reliable operation of the MOSFET relay, determine the limiting resistance value using the equation shown below when designing the circuit.

$$R1 = \frac{V_{CC} - V_{OL} - V_{F(ON)}}{I_{F(ON)}}$$

＊Make sure the $I_{F(ON)}$ is set at high value with safety margin. Refer to the catalogues of each model for the details of trigger LED forward operating current and recommended operating conditions of LED forward current.

· To ensure complete recovery of the MOSFET relay, calculate the value of release voltage using the equation shown below and make sure the voltage stays below the calculated value.

$$V_{F(OFF)} = V_{CC} - I_{F(OFF)}R1 - V_{OH}$$

＊Make sure the value of $I_{F(OFF)}$ is set lower than the release LED forward current indicated in the catalogues of each model and add safety margin.

· Add a bleeder resistor if the possible cause of the malfunction is coming from the leakage current in the transistor.

The CMOS drive circuit shown on the left is configured to have pins 1 and 2 maintained at approximately the same potential when switched to OFF mode, which offers exceptional noise immunity.

VOLTAGE SURGE (OUTPUT SIDE)

The effect of voltage surges (overvoltage conditions that exceed the absolute maximum rating even for a moment) on the MOSFET relay may cause damage to the output element.

Probable cause of failure

When the voltage surge superimposed on the output element (load circuit side) exceeds the load voltage V_{OFF} (absolute maximum rating), it may damage the output element of the MOSFET relay ultimately causing malfunction.

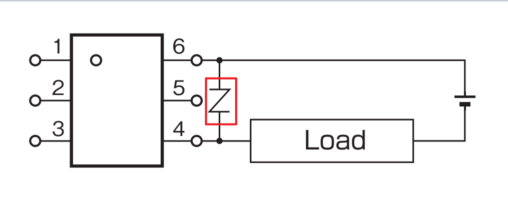
- Short-circuit fault in output element (refer to P15 *Photos of Failure Event*)
  → The output of the relay begins to conduct load current when LED forward operating current (I_F) is NOT applied across the input terminals (short-mode failure)
- Open-circuit fault in output element (refer to P16 *Photos of Failure Event*)
  → The output of the relay does NOT conduct load current when LED forward operating current ($_{IF}$) is applied across the input terminals (open-circuit failure)

■ Sources of voltage surge

(1) Electro-static discharge: ESD (human contact, contact with equipment surfaces)
(2) Transient originated from inside the electrical circuit or equipment
(3) Lightning

COUNTERMEASURE

■ Connect varistor across the output side terminals



■ How to select the right varistor

The voltage of the varistor must not exceed the load voltage (V_{OFF}) of MOSFET relay.

· For ESD protection, multilayer chip varistor is most commonly used.

· Please refer to the following table of varistor guidance when using commercial AC power supply.

Varistor guidance

Supply voltage	Recommended varistor voltage	Absolute maximum ratings V_{OFF}	Surge withstand capability
100 VAC line	220 to 270 V	400 to 600 V	1000 A or more
200 VAC line	430 to 470 V	600 V	1000 A or more

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RIPPLE VOLTAGE

When the current exceeds the absolute maximum ratings (voltage or current) due to the ripple in power supply, it may damage both the input and output elements.

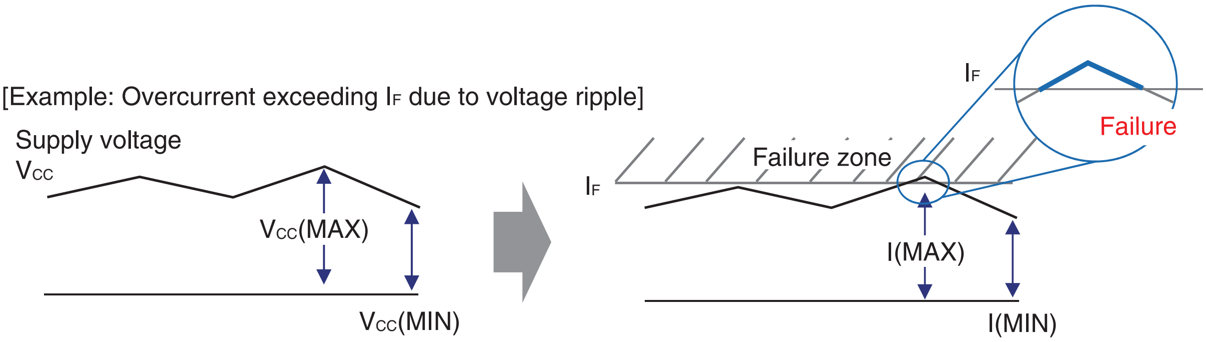
Probable cause of failure

Input side

When a current exceeding the maximum rated value of the LED forward current (I_F) flows across the input terminals affected by the maximum rated ripple of input voltage (V_{CC} (MAX)), it may damage the input light-emitting element (LED chip) ultimately causing malfunction.

- Short-circuit fault in LED chip (refer to P17 *Photos of Failure Event*)
  → The output of the relay does NOT conduct load current (does not turn ON) when LED forward operating current (I_F) is applied across the input terminals.
- Open-circuit fault in LED chip (refer to P17 *Photos of Failure Event*)
  → The output of the relay does NOT conduct load current (does not turn ON) when LED forward operating current (I_F) is applied across the input terminals.
  * The substantial drop in light output prevents from switching to ON mode.

[Example: Overcurrent exceeding I_F due to voltage ripple]



COUNTERMEASURE

Input ripple voltage must be considered to avoid exceeding the absolute maximum rated value of the LED forward current (I_F).

When the current exceeds the absolute maximum ratings (voltage or current) due to the ripple in power supply, it may damage both the input and output elements.

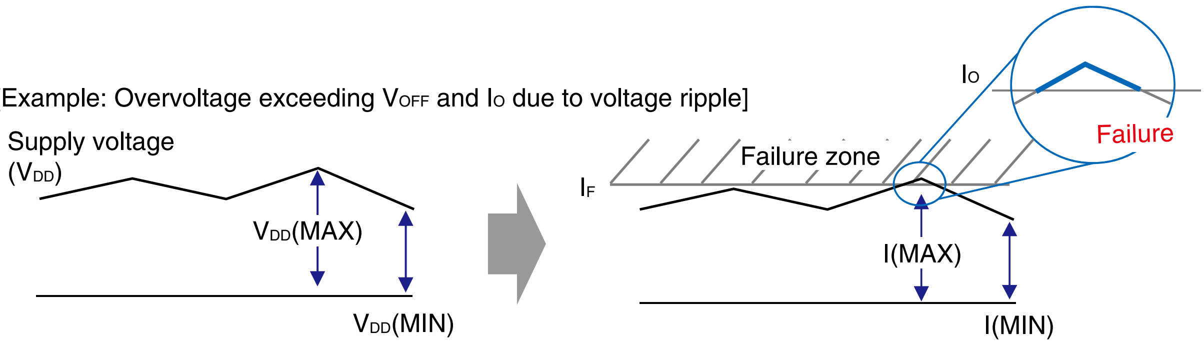
Probable cause of failure

Output side

When a voltage or current exceeding the absolute maximum rated values of output load voltage (V_{OFF}) and continuous load current (I_O) flows affected by the maximum rated ripple of input voltage (V_{CC} (MAX)), it may damage the output element ultimately causing malfunction.

- Short-circuit fault in output element (refer to P15 Photos of Failure Event)
  → The output of the relay begins to conduct load current when LED forward operating current (I_F) is NOT applied across the input terminals (short-mode failure)
- Open-circuit fault in output element (refer to P16 Photos of Failure Event)
  → The output of the relay does NOT conduct load current when LED forward operating current (I_F) is applied across the input terminals (open-circuit failure)

[Example: Overvoltage exceeding V_{OFF} and I_O due to voltage ripple]



COUNTERMEASURE

Output ripple voltage must be considered to avoid exceeding the absolute maximum rated values of load voltage (V_{OFF}) and continuous load current (I_O).

INRUSH CURRENT

Inrush current exceeding the absolute maximum rated value may occur when switching the MOSFET relay. This depends on the types of loads causing damage to the output element.

Probable cause of failure

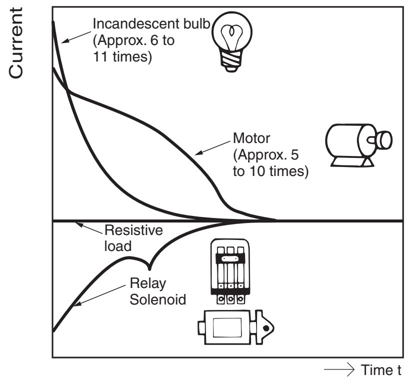
Inrush current occurs when the MOSFET relay is switched. When the inrush current exceeds the pulse on-state current (I_{OP}) of the MOSFET relay, it may damage the output element.
(Pulse condition: t=100 ms, Duty=1/10)

The inrush current varies with the load type. Typical loads are indicated below.

1. **Heater load (resistive load)**
   Resistive loads have very little inrush current (close to none). However, please note that resistance value varies with temperature in certain types of heaters, which may cause inrush current to occur under ambient temperature when the resistance value is low.

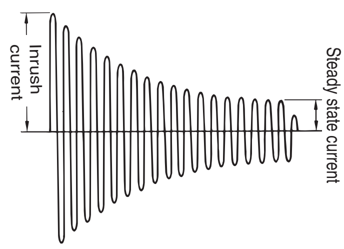
   <Types of heater with possible inrush current>
   - Pure metal heater (approximately 3 to 5 times of the rated current)
   - Ceramic heater (approximately 3 to 5 times of the rated current)
2. **Solenoid (only under AC power)**
   The inrush current is approximately 10 times the rated current.
3. **Mechanical relay (only under AC power)**
   The inrush current is approximately 2 to 3 times the rated current.
4. **Motors**
   Inductive loads such as motors have inrush current of approximately 5 to 10 times the rated current at start-up.

■ DC loads and their inrush currents



■ AC loads and their inrush currents

Load types	Inrush current/Steady state current	Waveform
Solenoid	Approx. 10 times	
Incandescent bulb	Approx. 10 to 15 times	
Motor	Approx. 5 to 10 times	
Relay	Approx. 2 to 3 times	
Capacitor	Approx. 20 to 50 times	
Resistive load	1	



COUNTERMEASURE

Make sure to confirm the amount of inrush current that flows into the load and select a product that does not exceed the pulse on-state current (I_{OP}) of the MOSFET relay.
(Pulse condition: t=100 ms, Duty=1/10)

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OUTPUT CIRCUIT DESIGN GUIDELINE (AMBIENT TEMPERATURE)

Continuous load current on the output side (I_O) stipulates its reduction rate according to temperature. When the current exceeds the specified rate, it may damage the output element.

Probable cause of failure

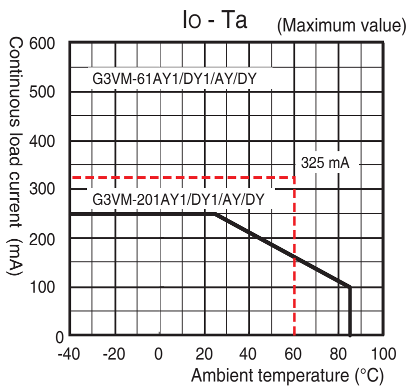
The reduction rate of continuous load current (I_O), according to the increasing ambient temperature, is specified based on the connection temperature rating (Tj=Allowable temperature rating in which the connection of internal element can withstand). When a current flows into the output exceeding the specified rate under high temperature condition, the connection temperature surpasses its rating causing damage to the output element.

Case: Continuous load current (I_O) had flown into the output exceeding the specified rate under high temperature condition

(Case study)
We needed output current flow of 400 mA. So, we selected a 500 mA (Ta=25°C) relay that allows the output side to have 25% margin of continuous load current (I_O).
The prototype test results were good, showing normal operation.
(The MOSFET relay during the trial test was used under room temperature of 25°C)
Malfunction occurred after the product was launched into the market.

(Cause)
In actual use, the temperature around the MOSFET relay was 60°C, so the current was over the continuous load current (I_O) stipulated in the "Continuous load current - Ambient temperature" graph.

(Conclusion)
The specified continuous load current (I_O) changes according to ambient temperature as shown on the right graph.
According to the graph, the MOSFET relay used this time under the ambient temperature condition of 60°C should be 325 mA for continuous load current (I_O).
With current of 400 mA, it exceeded its specified rate ultimately causing the product in the market to malfunction.



COUNTERMEASURE

Please make sure to check the continuous load current rates in relation to ambient temperature specified for each model by referring to the Graph: *Continuous Load Current with Ambient Temperature* and select a suitable MOSFET relay (with safety margin) to make sure the product is used under the allowable room temperature of the relay.

INPUT CIRCUIT DESIGN GUIDELINE (I_F)

Lack of LED forward operating current (I_F) caused by “drop in light output due to age-related degradation of input LED” of MOSFET relay and “increased room temperature” may cause the MOSFET relay to malfunction.

Probable cause of failure

The LED forward operating current (I_F) designed for the input circuit must be determined by considering several factors . These include : LED aging and temperature changes, as well as power supply variation with respect to the trigger LED forward current (I_{FT}). Otherwise, the input current will fall short due to the changes in environment and the amount of usage time, ultimately damaging the MOSFET relay. (Events of failure is shown on P13 and P14)

COUNTERMEASURE

Temperature derating considerations (shown below) are recommended at the time of the initial design stage to determine the LED forward operating current (I_F).

[How to design the trigger LED forward current value (I_{FT})]

Design value of trigger LED forward current (I_F) = I_{FT} (maximum value) ×α1×α2× (α3)

α1: LED aging rate → Differs by model (the type of LED used). Refer to the “expected service life” indicated in the catalogue under the precaution page.

α2: Ambient temperature change → Refer to the Graph: *Trigger LED Forward Current with Ambient Temperature* indicated in the catalogue.

α3: Safety factor → Degree of safety margin for power supply variation and degradation.

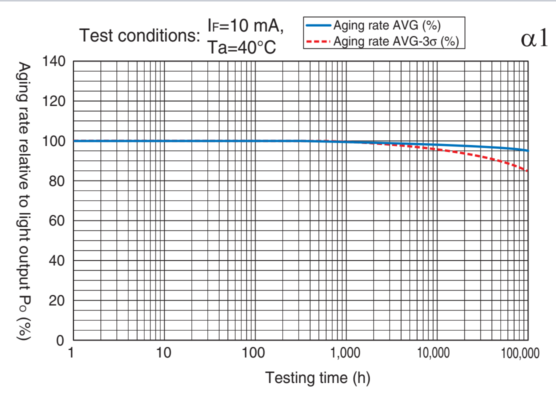
(Example) G3VM-401G, at maximum room temperature of 85°C

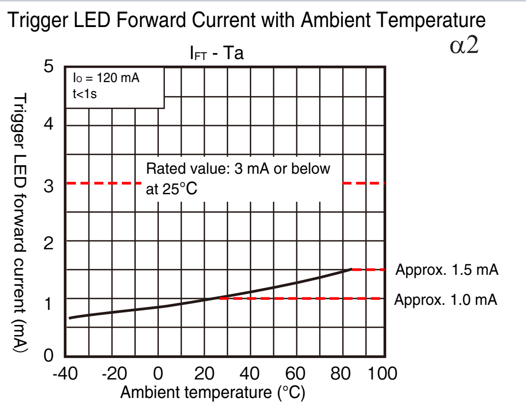
I_{FT}: 3 mA (maximum rated value, at 25°C)

α1: Set for 80% (20% reduction) after 100,000 hours of useful life based on the data of LED’s expected life expectancy → 1÷0.8 = 1.25
(When room temperature rises, aging accelerates. Therefore the aging rate increases more at 85°C compared to the data at 40°C. However, the rate will slow down if used under the condition that is lower than the I_F condition of 10 mA. 80% is set considering this point.)

α2: Set the aging rate based on the values of room temperature at 20°C and 85°C referring to the Graph: *Trigger LED Forward Current with Ambient Temperature*
→ 1.5 m÷1 mA = 1.5

Design value = 3 mA×1.25×1.5 (× α3) = approx. 5.6 mA (× α3)





INPUT CIRCUIT DESIGN GUIDELINE (LED AGING DEGRADATION AND AMBIENT TEMPERATURE)

Lack of LED forward operating current (I_F) caused by “drop in light output due to age-related degradation of input LED” of MOSFET relay and “increased room temperature” may cause the MOSFET relay to malfunction.

Probable cause of failure

Failure event 1. Lack of trigger LED forward current (I_{FT}) due to age-related degradation of input LED

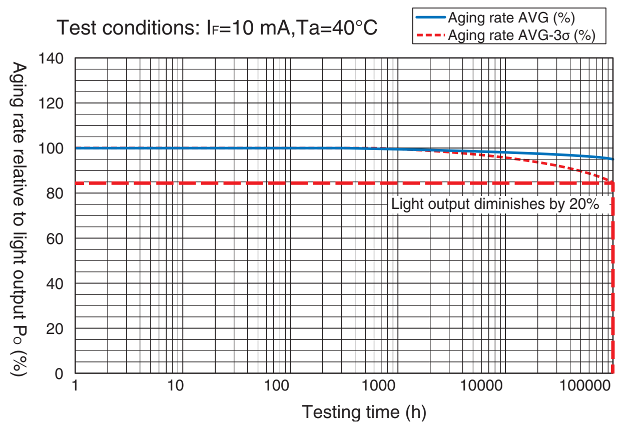
(Case study)
We needed input current of 3.5 mA. So, we selected a model (G3VM-401G) with the maximum trigger LED forward current (I_{FT}) rating of 3 mA (Ta=25°C) with safety margin.
The prototype test results were good, showing normal operation.
Malfunction had occurred after the product was launched into the market and running for 100,000 hours.

(Cause)
Light output stipulated in the Graph: *Expected Aging Data* had diminished during actual use, increasing the trigger LED forward current (I_{FT}) which led to the shortage in LED forward current and ultimately causing malfunction.

(Conclusion)
Light output diminishes according to the input side of the LED’s running time as shown in the graph below.
The graph indicates approximately 20% of light output drop when running for 100,000 hours at I_F=10 mA.
I_{FT} apparently increases by 25% (✻) when the light output diminishes by 20%.
The trigger LED forward current (I_{FT}) increases to 3.75 mA causing lack of LED forward operating current (I_F) of 3.5 mA ultimately causing the product in the market to malfunction.

✻ Equation
1/(100-20) = 1.25 (125%)

Example: G3VM-401G
I_{FT} =3 mA→3.75 mA



COUNTERMEASURE

The input current must be designed based on the maximum rating of the LED forward operation current (I_{FT}) and must take into account the decline in the LED light output associated with the operating time.

Lack of LED forward operating current (I_F)caused by “drop in light output due to age-related degradation of input LED” of MOSFET relay and “increased room temperature” may cause the MOSFET relay to malfunction.

Probable cause of failure

Failure event 2. Relay stopped working due to the lack of LED forward current (I_F) under high temperature condition.

(Case study)

We selected a model with 1 mA of design current (input side) because the standard value of the trigger LED forward current was 1 mA (Ta=25°C).

The prototype test results were good, showing normal operation.

(The MOSFET relay during the trial test was used under room temperature of 25°C)

Malfunction occurred after the product was launched into the market.

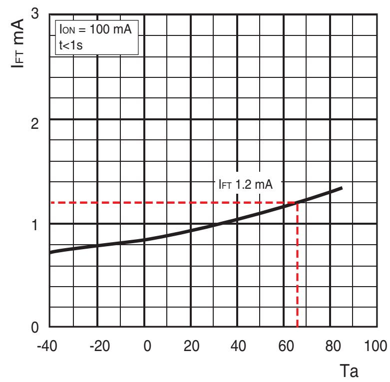
Item	Symbol	---	---	Unit
Trigger LED forward current	I_{FT}	Standard	1	mA
		Maximum	3	

(Cause)

The MOSFET relay was used under actual room temperature of 60°C causing the trigger LED forward current (I_{FT}) stipulated in the Graph: *LED Current with Ambient Temperature* to rise and the LED forward current (I_F) to fall short resulting to malfunction.

(Conclusion)

The trigger LED forward current (I_{FT}) changes according to ambient temperature as shown on the right graph. The MOSFET relay used this time under ambient temperature of 60°C is specified at 1.2 mA for I_{FT} exceeding the current of 1 mA (1 mA < 1.2 mA) causing the product in the market to malfunction.

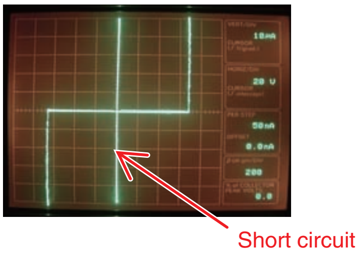
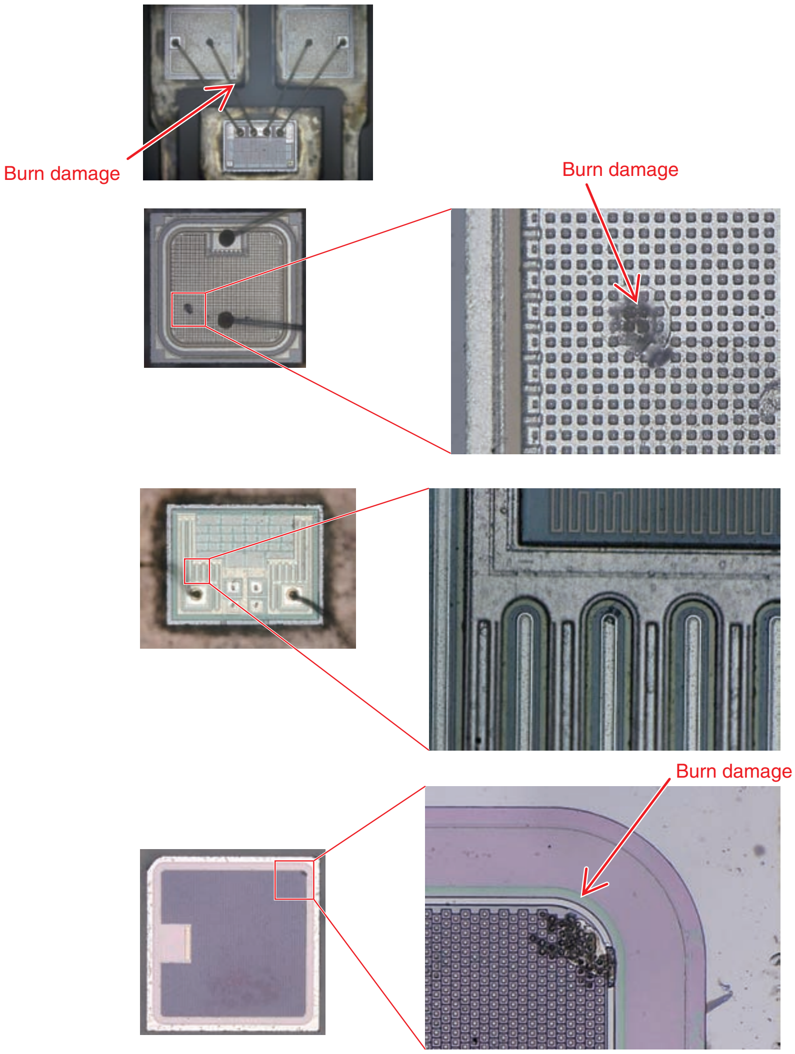
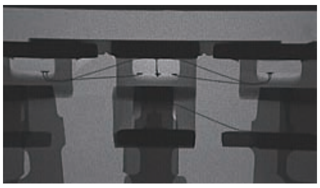


COUNTERMEASURE

The input current must be designed based on the maximum value of the trigger LED forward current and taking into account the changes in ambient temperature.

PHOTOS OF FAILURE EVENT (OUTPUT)

Output short circuit fault

Failure characteristics	Condition of output element
	
X-ray image of the interior	
 No anomalies	

PHOTOS OF FAILURE EVENT (OUTPUT)

Output open circuit fault

<table>
<tr><th>Exterior</th><th>Condition of output element</th></tr>
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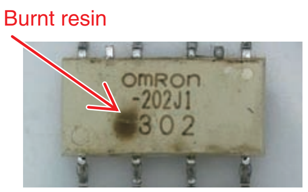

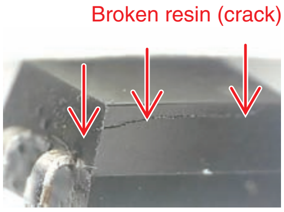

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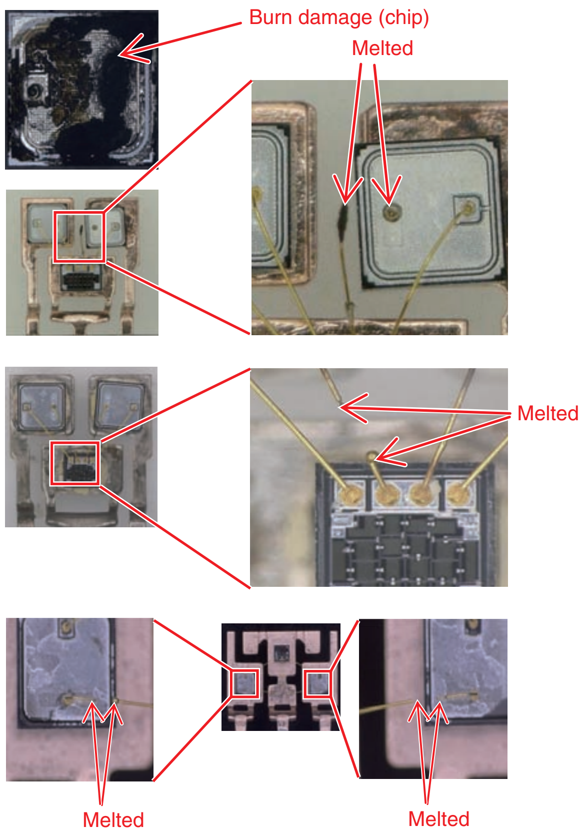
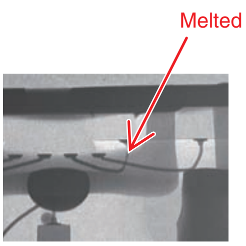
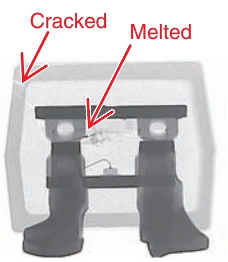


</td></tr>
<tr><td>X-ray image of the interior</td></tr>
<tr><td>




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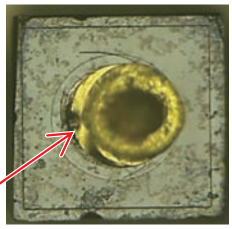
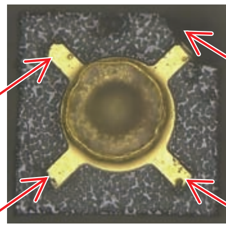
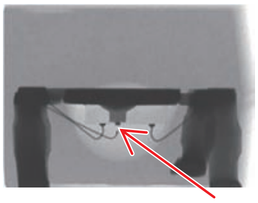
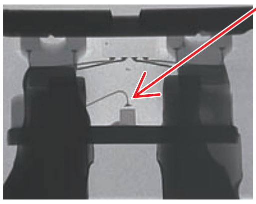
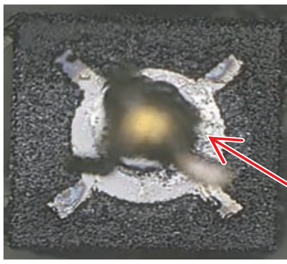
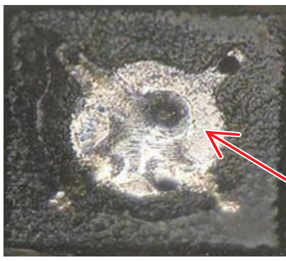
PHOTOS OF FAILURE EVENT (INPUT)

Input short circuit fault

Failure characteristics	Condition of input light-emitting element
	 

Input open circuit fault

Failure characteristic	Condition of input light-emitting element
 	 

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Offices

AUSTRIA
Schönbrunner Str. 297-307
A-1120 Vienna
Phone: +43 1 86642 0
Fax: +43 1 86642 250
wien@avnet-abacus.eu

BELARUS
c/o Avnet Abacus Russia
Office 24, Building 2
10 Korovinskoye Shosse,
127486 Moscow
Phone: +7 (495) 737 3688
Fax: +7 (495) 737 3686
belarus@avnet-abacus.eu

BELGIUM
De Kleetlaan 3
1831 Diegem
Phone: +32 2 227 2000
diegem@avnet-abacus.eu

BULGARIA
c/o Avnet Abacus Romania
4 Gara Herastrau,
Building B, 2nd Floor RO-020334
Bucharest
Phone: +4021 528 16 90
bulgaria@avnet-abacus.eu

CROATIA
c/o Avnet Abacus Slovenia
Dunajska Cesta 167
1000 Ljubljana
Phone: +386 (0)1 560 97 54
Fax: +386 (0)1 560 98 78
croatia@avnet-abacus.eu

CZECH REPUBLIC
Amazon Court Karolinska 661/4
CZ-18600 Prague Czech Republic
Phone: +420 234 091 011
Fax: +420 234 091 010
praha@avnet-abacus.eu

DENMARK
Knudlundvej 24 DK-8653 Them
Phone: +45 86 84 84 84
Fax: +45 86 84 82 44
them@avnet-abacus.eu

Lyskær 9, DK-2730 Herlev
Phone: +45 86 84 84 84
Fax: +45 43 29 37 00
herlev@avnet-abacus.eu

EGYPT
c/o Avnet Abacus Turkey
Tatlısu Mahallesi Pakdil
Sokak No: 7 Kat: 2 34774
Umraniye Istanbul Turkiye
Phone: +90 216 52 88 370
Fax: +90 216 52 88 377
egypt@avnet-abacus.eu

ESTONIA
Suur-Jõe 63, Pärnu,
80042 Pärnu Maakond,
Estonia
Phone: +372 56637737
paernu@avnet-abacus.eu

FINLAND
Pihatörmä 1 B
FI-02240 Espoo
Phone: +358 (0) 207 499 220
Fax: +358 (0) 207 499 240
espoo@avnet- abacus.eu

FRANCE
Immeuble Carnot Plaza
14 Avenue Carnot
91349 Massy Cedex, Paris
Phone: +33 (0) 1 6447 2929
Fax: +33 (0) 1 6447 9150
paris@avnet-abacus.eu

8 chemin de la Terrasse
Bat D 1er étage
31500 Toulouse
Phone: +33 (0) 5 6247 4787
Fax: +33 (0) 5 6247 4761
toulouse@avnet-abacus.eu

35 avenue des Peupliers
Les Peupliers2
35510 Cesson
Phone: +33 (0) 2 9983 7720
Fax: +33 (0) 2 9983 4829
rennes@avnet-abacus.eu

Parc Club du Moulin à Vent
Bât 10, 33 rue du Dr. G Lévy
F-69693 Vénissieux Cedex, Lyon
Phone: +33 (0) 4 7877 1370
Fax: +33 (0) 4 7877 1391
lyon@avnet-abacus.eu

GERMANY
Englische Str. 27
D – 10587 Berlin
Phone: +49 (0) 30 790 997 0
Fax: +49 (0) 30 790997 51
berlin@avnet-abacus.eu

Industriestr. 26
D-76297 Stutensee
Phone: +49 (0)7249 910 149
Fax: +49 (0)7249 910 177
stutensee@avnet-abacus.eu

Wilhelmstr. 1,
D-59439 Holzwickede / Dortmund
Phone: +49 (0) 2301 2959 27
Fax: +49 (0) 2301 2959 29
dortmund@avnet-abacus.eu

Oehleckerring 9a – 13 22419
Hamburg
Phone: +49 (0) 40 608 23 59 0
Fax: +49 (0) 40 608 23 59 20
hamburg@avnet-abacus.eu

Gruber Str. 60c-60d
D-85586 Poing / Munich
Phone: +49 (0) 8121 777 03
Fax: +49 (0) 8121 777 531
muenchen@avnet-abacus.eu

Lina-Ammon-Str. 19 b
D-90471 Nürnberg
Phone: +49 (0) 911 244 250
Fax: +49 (0) 911 244 25 25
nuernberg@avnet-abacus.eu

Gutenbergstr. 15
D-70771 Leinfelden- Echterdingen
/ Stuttgart
Phone: +49 (0) 711 78260 02
Fax: +49 (0) 711 78260 333
stuttgart@avnet-abacus.eu

Gaußstraße 10 D-31275 Lehrte
Phone: +49(0) 5132 5099 0
Fax: +49(0) 5132 5099 76
lehrte@avnet-abacus.eu

GREECE
c/o Abacus Avnet Serbia
Milentija Popovića 5B,
Floors 6-8 Belgrade RS11070
Phone: +381 11 4022302
Fax: +381 11 4049900
belgrade@avnet-abacus.eu

HUNGARY
c/o Avnet Abacus Czech Republic
GreenPoint Offices,
Blok F Turcianska 2 SK-82109,
Bratislava
Phone: +421 232 242 608
Fax: +421 2 32 1111 40
budapest@avnet-abacus.eu

IRELAND
c/o Avnet Abacus Bolton
Oceanic Building
Waters Meeting Road
Bolton BL1 8SW
Phone: +44 (0)1204 547170
Fax: +44 (0)1204 547171
bolton@avnet.eu

ISRAEL
Avnet Components Israel Ltd.
P.O. Box 48
Tel-Mond, 4065001
Phone: 972-9-7780280
Fax: 972-3-760-1115
avnet.israel@avnet.com

ITALY
Via Manzoni 44
I-20095 Cusano Milanino (Milano)
Phone: +39 02 660 921
Fax: +39 02 66092 332
milano@avnet-abacus.eu

Viale dell'industria 23
I-35129 Padova
Phone: +39 049 7800 381
Fax: +39 049 7730 36
padova@avnet-abacus.eu

Via di Settebagni, 390
I-00138 Roma
Phone: +396-41231951
roma@avnet-abacus.eu

Via Scaglia Est, 31/33
41126 Modena
Phone: +39 059 34891
Fax: +39 059 344993
modena@avnet-abacus.eu

Via Panciatichi 40/11
I-50127 Firenze
Phone: +39 055 436 1928
Fax: +39 055 428 8810
firenze@avnet-abacus.eu

LATVIA
c/o Avnet Abacus Poland
Plac Solny 16
PL-50-062 Wroclaw
Phone: +48 71 34 205 99
Fax: +48 71 34 229 10
latvia@avnet-abacus.eu

LITHIUANIA
c/o Avnet Abacus Poland
Plac Solny 16
PL-50-062 Wroclaw
Phone: +48 71 34 205 99
Fax: +48 71 34 229 10
lithuania@avnet-abacus.eu

NETHERLANDS
Stadionstraat 2, 6th fl.
NL-4815 NG Breda
Phone: +31 (0) 76 57 22 300
Fax: +31 (0) 76 57 22 303
breda@avnet-abacus.eu

NORWAY
Olaf Helsetsvei 6,
0694 Oslo Norway
Phone: +47 (0) 94 89 53 73
oslo@avnet-abacus.eu

POLAND
Plac Solny 16
PL-50-062 Wroclaw
Phone: +48 71 34 205 99
Fax: +48 71 34 229 10
wroclaw@avnet-abacus.eu

PORTUGAL
Tower Plaza, Rot. Eng.
Edgar Cardoso,
23, Pl. 14, Sala E
PT-4400-676 Vila Nova de Gaia
Phone: +351 223 779502
Fax: +351 223 779503
portugal@avnet-abacus.eu

ROMANIA
4 Gara Herastrau, Building B,
2nd Floor
RO-020334 Bucharest
Phone: +4021 528 16 90
romania@avnet-abacus.eu

RUSSIA
49A Tatischeva Street,
Ekaterinburg
RUS-620028
Phone: +7 (912) 650 1944
Ekaterinburg@avnet- abacus.eu

Office 24, Building 2
10 Korovinskoye Shosse
127486 Moscow
Phone: +7 (495) 737 3688
Fax: +7 (495) 737 3686
Moscow@avnet-abacus.eu

SERBIA
Milentija Popovića 5B, Floors 6-8
Belgrade RS11070
Phone: +381 11 4022302
Fax: +381 11 4049900
belgrade@avnet-abacus.eu

SLOVAKIA
GreenPoint Offices, Blok F
Turcianska 2
SK-82109, Bratislava
Phone: +421 232 242 608
Fax: +421 2 32 1111 40
slovakia@avnet-abacus.eu

SLOVENIA
Dunajska Cesta 167
1000 Ljubljana
Phone: +386 (0)1 560 97 54
Fax: +386 (0)1 560 98 78
ljubljana@avnet-abacus.eu

SOUTH AFRICA
First Floor, Forrest House
Belmont Office Park
Belmont Road,
Rondebosch 7700, Cape Town
Phone: +27 (0) 21 689 4141
Fax: +27 (0) 21 686 4709
sales@avnet.co.za

11 Forest Square, Suite 4,
Bauhinia Building, Derby Place,
Westville, 3629, Durban
Phone: +27 (0) 31 266 8104
Fax: +27 (0) 31 266 1891
sales@avnet.co.za

Block 13, Pinewood Office Park
33 Riley Road Woodmead,
2191 Sandton, Johannesburg
Phone: +27 (0) 11 319 8600
Fax: +27 (0) 11 319 8650
sales@avnet.co.za

SPAIN
NyN Tower, C/ Tarragona,
149-157, Floor 19
ES-08014 Barcelona
Phone: +34 (0) 93 327 85 50
Fax: +34 (0) 93 425 05 44
barcelona@avnet-abacus.eu

Plaza Zabalgane 12 Bajo Izda,
Galdakao / Vizcaya
ES -48960 Bilbao
Phone: +34 (0) 94 457 0044
Fax: +34 (0) 94 456 8855
bilbao@avnet-abacus.eu

C/Chile, 10 2ª Plta. Oficina 229
ES -28290 Las Matas / Madrid
Phone: +34 (0) 913 72 7200
Fax: +34 (0) 916 36 9788
madrid@avnet-abacus.eu

SWEDEN
Löfströms Allé 5,
Sundbyberg, Box 1830,
SE-171 27 Solna
Phone: +46 (0) 858 746200
Fax: +46 (0) 858 746 001
stockholm@avnet-abacus.eu

Smörhålevägen 3
SE-43442 Kungsbacka
Phone: +46 (0)8 58746 200
Fax: +46 (0)300 140 15
gothenburg@avnet-abacus.eu

SWITZERLAND
Bernstrasse 392
CH-8953 Dietikon
Phone: +41 (0) 43 322 49 90
Fax: +41 (0) 43 322 49 99
zurich@avnet-abacus.eu

TURKEY
Tatlısu Mahallesi Pakdil
Sokak No: 7 Kat: 2 34774
Umraniye Istanbul Turkiye
Phone: +90 216 52 88 370
Fax: +90 216 52 88 377
istanbul@avnet-abacus.eu

UK
First Floor, The Gatehouse
Gatehouse Road Aylesbury,
Bucks HP19 8DB
Phone: +44 (0) 1296 678920
Fax: +44 (0) 1296 678939
Aylesbury@avnet.eu

Building 5 Waltham Park
White Waltham, Maidenhead
Berkshire SL6 3TN
Phone: +44 (0)1628 512900
Fax: +44 (0)1628 512999
maidenhead@avnet.eu

Avnet House
Rutherford Close
Meadway, Stevenage
Hertfordshire SG1 2EF
Phone: +44 (0)1438 788 500
Fax: +44 (0)1438 788 250
stevenage@avnet.eu

Oceanic Building
Waters Meeting Road
Bolton BL1 8SW
Phone: +44 (0)1204 547170
Fax: +44 (0)1204 547171
bolton@avnet.eu

UKRAINE
c/o Avnet Abacus Poland
Plac Solny 16
PL-50-062 Wroclaw
Phone: +48 71 34 205 99
Fax: +48 71 34 229 10
ukraine@avnet-abacus.eu