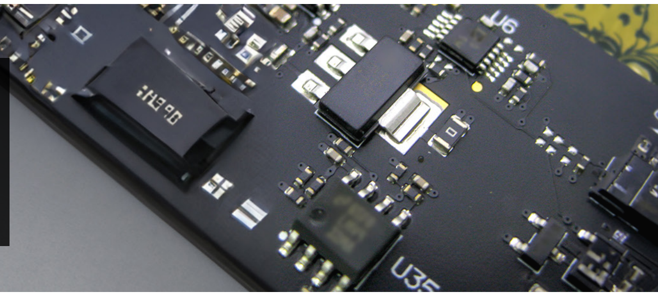
Depletion-Mode MOSFETs and Applications



Objectives

The primary objective of this application note is to enhance the comprehension and understanding of depletion-mode, N-Channel Vertical MOSFET and how it is used in various applications. Numerous examples provide detailed equations that designers can use to design simple voltage regulators, constant current sources, high voltage ramp generators, and power supply start-up circuits. The information presented here highlights many solutions to challenging engineering problems.

Applications

This application note is applicable to many scenarios where depletion-mode, N-Channel MOSFETs are utilized.

Target Audience

This document is intended for designers and developers who are utilizing Depletion MOSFETs within their respective applications.

Contact Information

For more information, contact the Littelfuse Power Semiconductor team of product and applications experts:

- APAC_PowerSemi_Tech@Littelfuse.com
- CSA_PowerSemi_Tech@Littelfuse.com
- EMEA_PowerSemi_Tech@Littelfuse.com
- NA_PowerSemi_Tech@Littelfuse.com

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1. Introduction

Applications such as: constant current sources, normally closed solid state relays, and higher-voltage DC lines in various power systems require N-channel depletion-mode power MOSFETs, which operate as normally-on switches when the gate-to-source voltage is zero ($V_{GS} = 0\,V$). This paper describes our low-power N-channel depletion-mode MOSFETs, in a couple of application examples, to help designers select these devices for their applications.

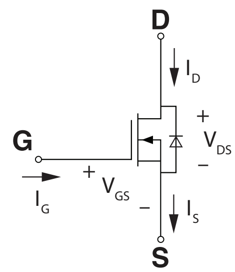

Figure 1. N-Channel Depletion-Mode MOSFET

The circuit symbol for an N-channel depletion-mode power MOSFET is shown in Figure 1. The terminals are named gate (G), source (S) and drain (D). Littelfuse low-power depletion-mode MOSFETs are built using a structure known as vertical double-diffused MOSFET (DMOSFET), which offers superior performance characteristics compared to other depletion-mode MOSFETs on the market. These advantages include high drain-to-source breakdown voltage (V_{DSX}), high current capability and an extended forward-biased safe operating area (FBSOA).

Figure 2 displays a typical graph of the drain current as a function of the drain-to-source voltage, known as drain current characteristic (I_D) versus the drain-to-source voltage (V_{DS}), known as the output characteristic. It resembles an N-channel enhancement-mode-power MOSFET plot, except that it has current lines at (V_{GS}) equal to –2 V, –1.5 V, –1 V, and 0 V.

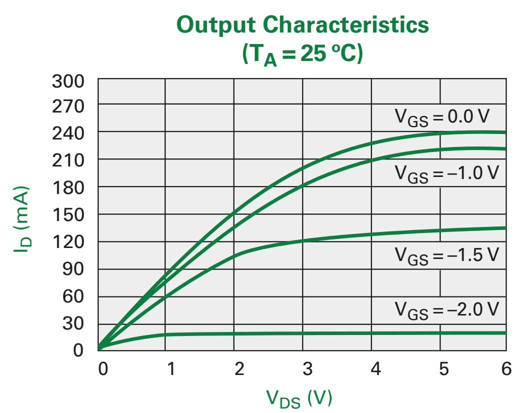

Figure 2. CPC3710 - MOSFET Output Characteristics

The on-state drain current (I_{DSS}), as defined in the data sheet, is the current that flows between the drain and the source at a specific drain-to-source voltage (V_{DS}), when the gate-to-source voltage (V_{GS}) is zero meaning that the gate is shorted the gate is shorted to the source. Applying a positive (V_{GS}) increases the device's current conduction, while a negative (V_{GS}) reduces the drain current.

As an example, the CPC3710 stops conducting drain current at $V_{GS} = -3.9$ V. This voltage is called the gate-to-source cutoff voltage, or threshold voltage ($V_{GS(off)}$). In order to ensure proper turn-on, the applied gate-to-source voltage (V_{GS}) voltage should be close to 0 V, and to properly turn-off, a gate voltage (V_{GS}) significantly lower than ($V_{GS(off)}$) should be applied. Theoretically, the on-state drain current ($I_{D(on)}$), can be defined as:

$$I_{D(on)} = I_{DSS} \cdot \left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2 \qquad \text{(Equation 1)}$$

Note that Equation 1 is a theoretical expression and, in most cases, will not yield an accurate drain current value. The $V_{GS(off)}$ ranges from –3.9 V to –1.4 V, and $I_{D(on)}$ is influenced by both $V_{GS(off)}$ and temperature.

A list of Littelfuse discrete N-channel low-power depletion-mode MOSFETs is given in Table 1. The table represents the five key parameters: (BV_{DSX}): the drain-to-source breakdown voltage, $R_{DS(on)}$: the on-state resistance, $V_{GS(off)\_Min}$ and $V_{GS(off)\_Max}$: the minimum and maximum gate-to-source cutoff voltages, and (I_{DSS_Min}): the minimum on-state drain current, along with standard discrete package options unnecessary, are being used in the entire document such as SOT-23, SOT-89, SOT-223 and SOT-223-2L.

Table 1. Littelfuse N-Channel Depletion-Mode MOSFETs

Part No.	BV_{DSX} (V)	$R_{DS(on)}$ (Ω)	$V_{GS(off)\_Min}$ (V)	$V_{GS(off)\_Max}$ (V)	I_{DSS_Min} (mA)	Package
CPC3701	60	1	–1.4	–3.1	600	SOT-89
CPC3703	250	4	–1.6	–3.9	360	SOT-89
CPC3708	350	14	–2.0	–3.6	130	SOT-89, SOT-223
CPC3710	250	10	–1.6	–3.9	220	SOT-89
CPC3714	350	14	–1.6	–3.9	240	SOT-89
CPC3720	250	22	–1.6	–3.9	130	SOT-89
CPC3730	350	35	–1.6	–3.9	140	SOT-89
CPC3902	250	2.5	–1.4	–3.1	400	SOT-89, SOT-223
CPC3909	400	6	–1.4	–3.1	300	SOT-89, SOT-223
CPC3960	600	44	–1.4	–3.1	100	SOT-223
CPC3980	800	45	–1.4	–3.1	100	SOT-223
CPC3981Z	800	45	–1.4	–3.1	100	SOT-223-2L
CPC3982	800	380	–1.4	–3.1	20	SOT-23

2. Selecting a Depletion-Mode MOSFET

Depletion-mode-power MOSFETs are ideally used in applications requiring a normally-on switch. Based on the application, the main selection criteria for a depletion-mode MOSFET are as follows:

1. Select the drain-to-source breakdown voltage (BV_{DSX}), meeting the margin for reliable operation. The application voltage must be lower than the drain-to-source breakdown voltage of the device. (BV_{DSX}) needs to be selected to accommodate the voltage swing between the positive and the negative buses, as well as any voltage peaks caused by voltage ringing, due to transients.

2. Identify the on-state drain current requirement (I_{DSS}) and pick a device capable of handling that current. The application current must be lower than the on-state drain saturation current (I_{DSS}) of the device. It is the maximum current that can flow between the drain and source, which occurs at a particular drain-to-source voltage (V_{DS}), and when the gate-to-source voltage (V_{GS}) is zero.

3. N-channel depletion-mode MOSFETs have a negative-cutoff voltage ($V_{GS(off)}$). A designer has to know the magnitude of the negative cutoff voltage (or threshold voltage). A negative gate-to-source voltage (V_{GS}) will reduce the drain current until the device's cutoff voltage level is reached and conduction ceases.

3. Applications

3.1. Current Source #1

Figure 3 shows a precise current source circuit supplying load resistor load R2. TL431 is a precision voltage reference IC. The feedback voltage across the sense resistor R3 is controlled to be 2.5 V. The circuit will operate as a current source at any current level below the CPC3710's rated current I_{DSS}. Note that at 200 V the MOSFET power dissipation will be 1 W.

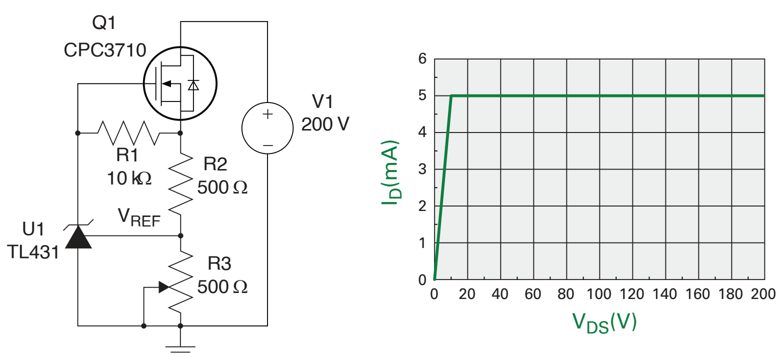

Figure 3. Depletion-Mode MOSFET Current Source Circuit and the Current Waveform

The theoretical sense resistor value is given by:

$$R3 \cong \frac{V_{REF}}{I_D} \qquad \text{(Equation 2)}$$

Where:

- $V_{REF} = 2.5$ V (TL431)
- $I_D = 5$ mA (Desired Current)

Note that Equation 2 is a theoretical formula that would probably not estimate the practical values of R3. In most cases, it is convenient to use a potentiometer to set the desired current level.

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3.2. Current Source #2

Figure 4 illustrates a current source circuit example with a voltage reference IC and a depletion-mode MOSFET (Q1), which compensates for supply voltage fluctuations. The current source provides a total current to the load comprising the set current through the resistor R_{SET}, and the IC quiescent current I_Q. This circuit provides precision current and ultra-high output impedance.

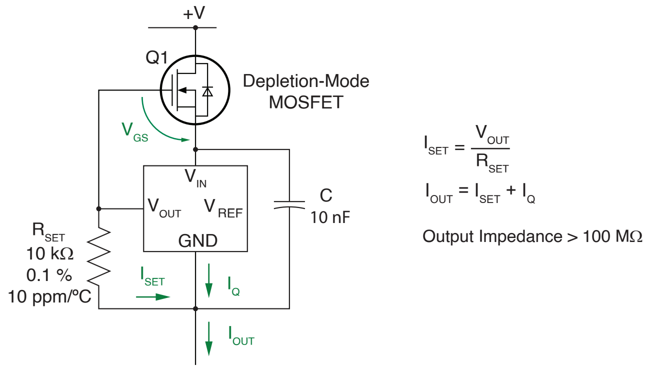

Figure 4. N-Channel Depletion-Mode MOSFET with a Voltage Reference to provide a Precise Current Source

3.3. Startup Circuit for Mains Powered Switch-Mode Power Supply

Many applications in industrial and consumer electronics require switch-mode-power supplies that operate from wide nominal mains voltage variations of 100 V_{AC} to 240 V_{AC}. Figure 5 shows a power supply that uses a depletion-mode MOSFET Q1, to kick-start operation from turn on, by providing initial power to the power factor correction IC (PFC), through Q1. Compared to a traditional resistor-splitter-startup circuit approach which consumes electrical power continuously, the depletion-mode MOSFET is only turned on during the initial startup sequence and by that it increases the Switch Mode Power Supply total efficiency.

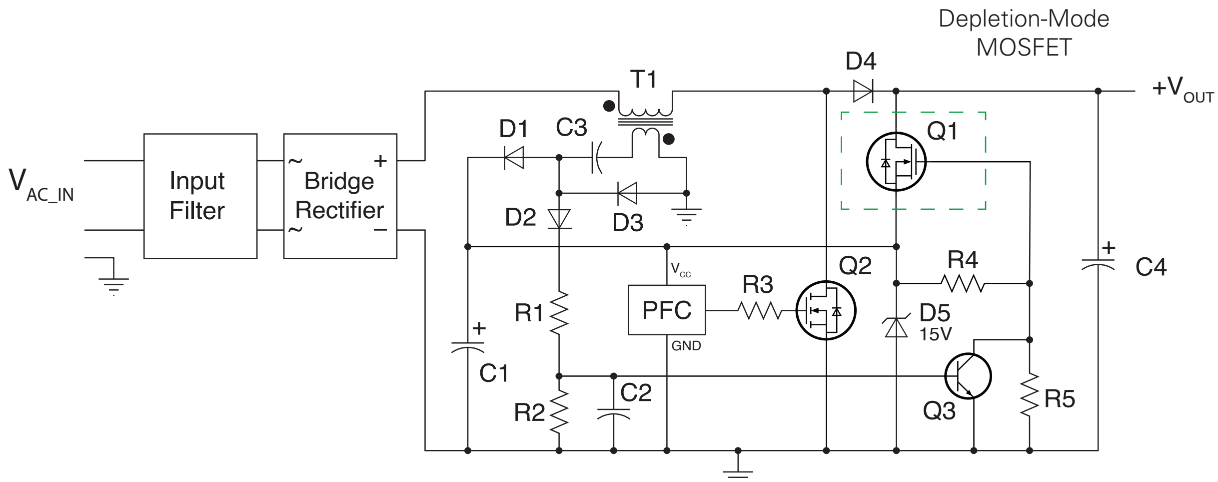

Figure 5. Power Supply Start-Up Circuit with Depletion-Mode MOSFET

Q1 provides initial power from the mains through Input Filter, Bridge Rectifier, T1, and D4. The voltage divider R4, R5 sets up an operation point to obtain the minimum required current from Q1. Zener diode D5 limits the supply voltage of the PFC IC to +15V. After the start-up, the secondary winding of boost transformer T1 generates the supply voltage for the PFC IC through D1, D2 and C3, and provides enough current through D2 and R1 to provide a high enough voltage to the base of Q3, to turn it on and clamp the gate of Q1 to ground.

3.4. Voltage Ramp Generator

Applications such as high-voltage-sweep circuits and automatic test equipment, require high-voltage ramps with a linear relationship between output voltage and time. The circuit shown in Figure 6 utilizes one depletion-mode MOSFET to design a voltage-ramp generator circuit.

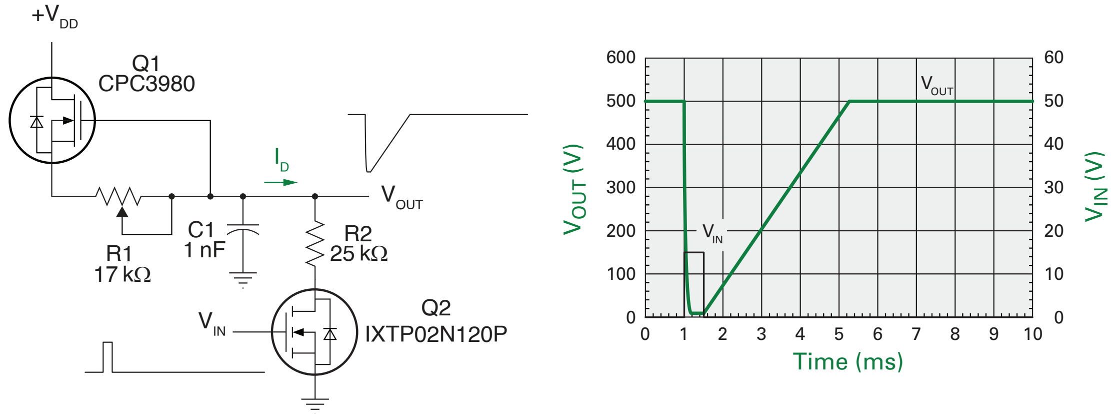

Figure 6. Power Supply Start-Up Circuit with Depletion-Mode MOSFET

Q1 is configured as a constant-current-source-charging capacitor C1. R1 provides negative feedback to regulate and set the desired current value. The constant-current source charges capacitor C1 and generates a voltage ramp V_{OUT} across the capacitor. Q2 can be turned on with a TTL or a CMOS control signal, to reset the ramp voltage by discharging the capacitor through resistor R2 to Ground. Resistor R2 limits the discharge current for Q2 to operate within its SOA rating.

Assume the ramp voltage:

$$\frac{dV}{dt} = 0.1\text{V/µs}$$

The value of capacitor C1 should be small enough to reduce excessive charging and discharging of energy, but large enough that output loads and stray capacitances will not introduce significant errors. C1 is chosen to be 1 nF.

The charging current is defined as:

$$I = C1 \cdot \frac{dV}{dt} \qquad \text{(Equation 3)}$$

$$I = 1\text{ nF} \cdot 0.1\text{ V/µs} = 100\text{ µA}$$

The value of R1 for a 100 µA current source can be approximated:

$$R1 \cong \frac{V_{GS}}{I_D} \cdot \left(\sqrt{\frac{I_D}{I_{DSS}}} - 1\right)$$

Where:

- V_{GS} = Pinch-off-voltage = –1.75 V at desired ($I_{DS(on)}$)
- I_{DSS} = 100 mA
- I_D = 100 µA (Desired Current)

$$R1 = \frac{-1.75\ \text{V}}{100\ \mu\text{A}} \cdot \left(\sqrt{\frac{100\ \mu\text{A}}{100\ \text{mA}}} - 1\right) \approx \frac{-1.75\ \text{V}}{100\ \mu\text{A}} \cdot (0.03162 - 1) \approx \frac{1.695\ \text{V}}{100\ \mu\text{A}} \approx 16.9\ \text{k}\Omega$$

Assume the switching frequency for Q2 is $f_{sw} = 200\,\text{Hz}$ and the discharge time is $t_{Discharge} = 100\,\mu\text{s}$

Power loss in the output capacitor C1:

$$P = \frac{1}{2} \cdot C1 \cdot (V_{OUT})^2 \cdot f_{sw} \qquad \text{(Equation 4)}$$

Using equation 4:

$$P = \frac{1}{2} \cdot 1\ \text{nF} \cdot (500\ \text{V})^2 \cdot 200\ \text{Hz} = 125\ \mu\text{J} \cdot 200\ \text{Hz} = 25\ \text{mJ/s} = 25\ \text{mW}$$

Discharge time:

$$t_{Discharge} = 4 \cdot R2 \cdot C1 \qquad \text{(Equation 5)}$$

Using equation 5:

$$R2 = \frac{100\ \mu\text{s}}{4 \cdot 1\ \text{nF}} = 25\ \text{k}\Omega$$

3.5. Linear Voltage Regulator

Many applications require a linear voltage regulator that operates from high input voltage, typically sourced from a wide nominal voltage range of 100 V_{AC} to 240 V_{AC}, with a maximum peak voltage of ±340 V. Applications such as CMOS ICs and small analog circuits require a 5 V to 15 V DC power supply that provides protection against fast-high-voltage transients and and maintains low quiescent current. Figure 7 displays a mains powered linear-voltage regulator using a depletion-mode MOSFET, which meets the requirements for low transient voltage and low quiescent current.

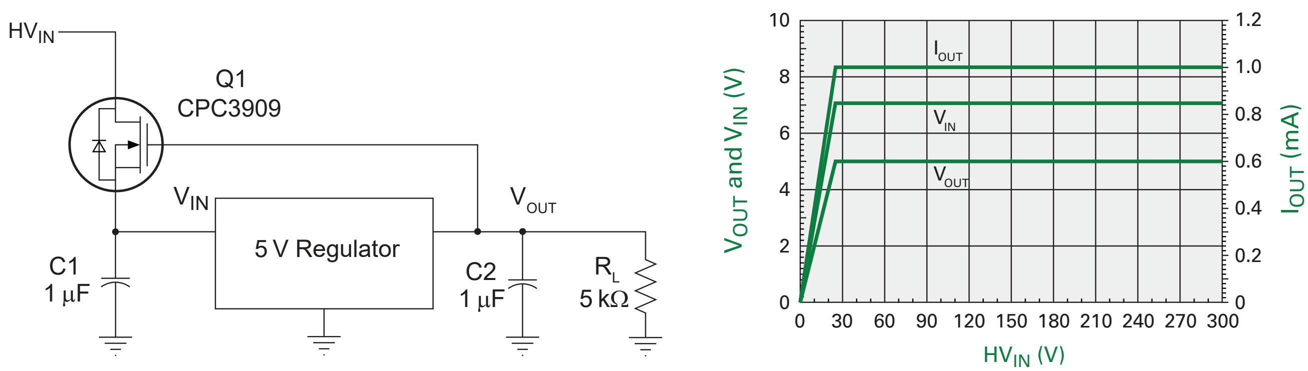

Figure 7. Mains Powered Linear Voltage Regulator

High voltage transients are generated in telecommunication circuits because of lightning and spurious radiation, and in automotive and avionics circuits because of inductive loads. Low-quiescent current is required to minimize power dissipation in these linear regulators.

HV_{IN} Calculation:

$$I_D = I_{DSS} \cdot \left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

Solving for V_{GS}:

$$V_{GS} = V_{GS(off)} \cdot \left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right)$$

Where:

- $V_{GS} = V_{OUT} - V_{IN}$

$$V_{IN} = V_{OUT} - V_{GS(off)} \cdot \left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right)$$

$$V_{IN} = 5\text{ V} + 2\text{ V} \cdot \left(1 - \sqrt{\frac{1\text{ mA}}{300\text{ mA}}}\right) \approx 5\text{ V} + 2\text{ V} \cdot (1 - 0.05774) \approx 6.885\text{ V}$$

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3.6. Current-Monitor Circuit

A simple current monitor circuit using an op-amp and a depletion-mode MOSFET is shown in Figure 8.
R1 monitors the current to the load and the MOSFET Q1 provides an output voltage proportional to the current being monitored.

$$V_{OUT} = I_{LOAD} \cdot \left(\frac{R2 \cdot R3}{R1}\right) \qquad \text{(Equation 6)}$$

Resistor R1 should have 0.1 % tolerance with an appropriate wattage rating.

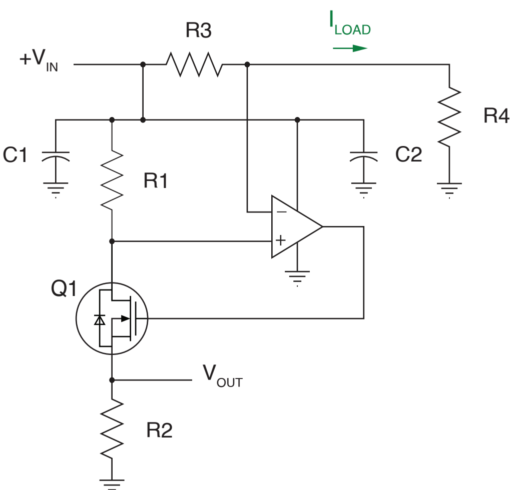

Figure 8. Current Monitor using Depletion-Mode MOSFET and a Single-Supply Op-Amp

For example:

- R1 = 100 Ω
- R2 = 1 kΩ
- R3 = 0.1 Ω

Using equation 6:

$$\frac{V_{OUT}}{I_{LOAD}} = \frac{R2 \cdot R3}{R1} = \frac{1000\,\Omega \cdot 0.1\,\Omega}{100\,\Omega} = 1\,\frac{V}{A}$$

3.7. Normally Closed Solid State Relay

Depletion-mode MOSFETs can be used to create normally-closed solid state relays, using Littelfuse's optical driver FDA217. Figure 9 shows a typical connection of two external CPC3980 depletion-mode MOSFETs, arranged in back-to-back configuration, controlled by an FDA217 photovoltaic isolator, which provides galvanic isolation and gate drive to make an AC/DC switch. FDA217 has internal turn-off circuitry, so that no external-bleed resistors are required.

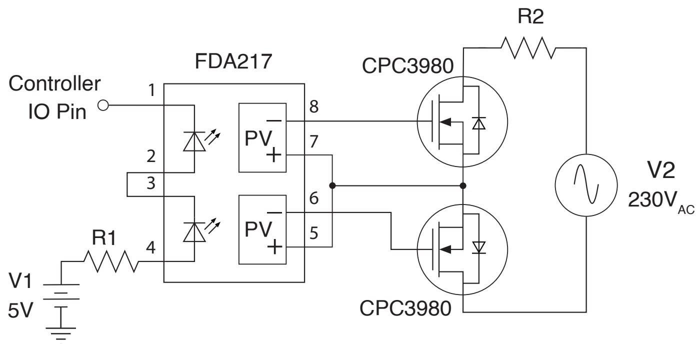

Figure 9. FDA217 used with CPC3980 MOSFETs to create Normally Closed Solid State Relay

3.8. Constant Current Source driving LED Strings

Figure 10 is showing how a depletion-mode MOSFET device is used to drive an array of multiple LEDs with a constant current. Since LEDs exhibit a non-linear voltage-current characteristic, driving them with a constant current ensures uniform light output without visible variation.

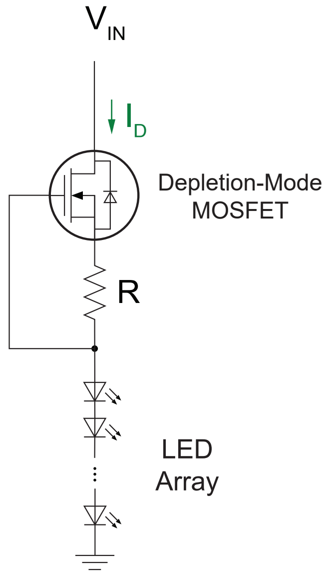

Figure 10. Depletion MOSFET driving LED array with a constant current

Working principle:

- Depletion-mode MOSFET provides constant current to the load depending on resistor R
- The current I_D is independent from the input voltage V_{IN}
- The constant current I_D is equivalent to:

$$I_D \approx \frac{V_{GS(off)}}{R}$$

Possible applications for constant current sources:

- LED array driver
- Trickle charge circuit to maintain battery charge
- Charge capacitors at constant rate

With long LED strips as illustraited in Figure 11, all LEDs are expected to produce uniform visible light output. However, one challenge that needs to be addressed, is the voltage drop due to resistive losses over the long LED strip. Driving all LEDs in that strip with a constant current ensures consistent brightness across the entire strip. Depletion-mode MOSFETs are ideal to create constant-current sources.

The circuit example illustrates how the voltage drops created by the resistive losses over the long LED strip are equalized by the constant-current sources. All resistors R1 through Rn have the same resistor value. All LEDs will have the same visible brightness.

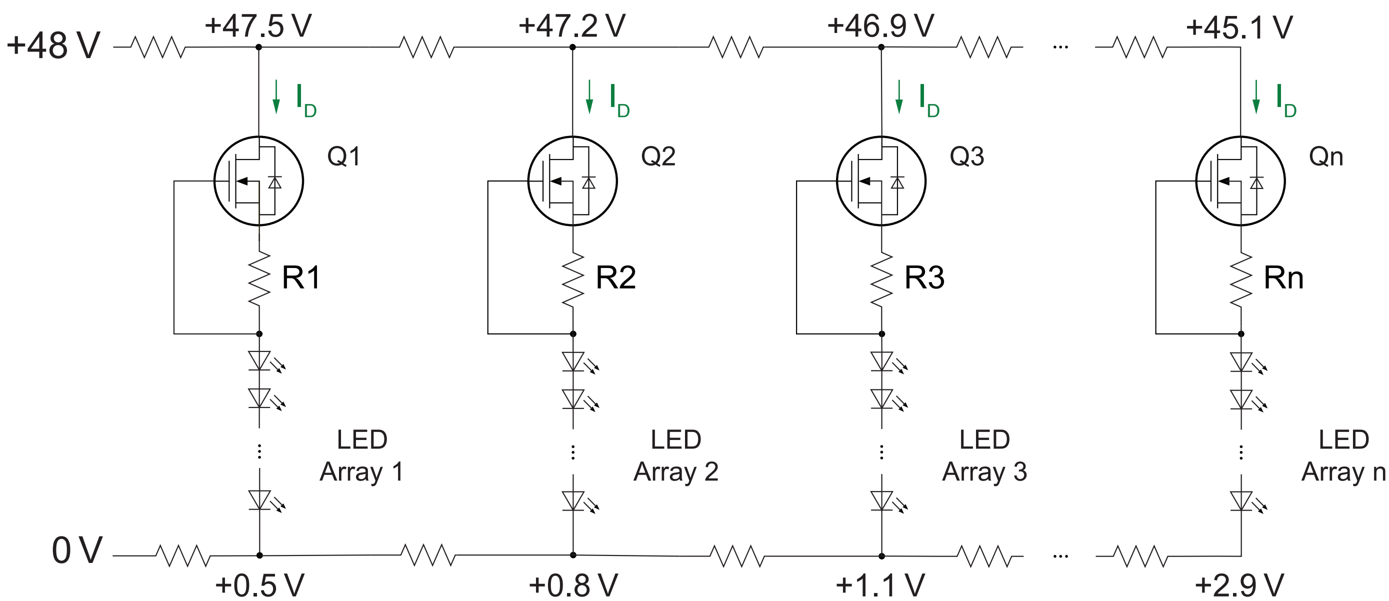

Figure 11. LED strip with multiple LED arrays driven with constant current

Revision History

Date	Revision	Changes
October 2025	04	Transferred Application Note content to LF template. Added new Section 3: Constant Current Source Driving LED Strings.