# CS51031

# Fast PFET Buck Controller

## Description

The CS51031 is a switching controller for use in DC-DC converters. It can be used in the buck topology with a minimum number of external components. The CS51031 consists of a $V_{CC}$ monitor for controlling the state of the device, 1.0A power driver for controlling the gate of a discrete P-channel transistor, fixed frequency oscillator, short circuit protection timer, programmable soft start, precision reference, fast output voltage monitoring comparator, and output stage driver logic with latch.

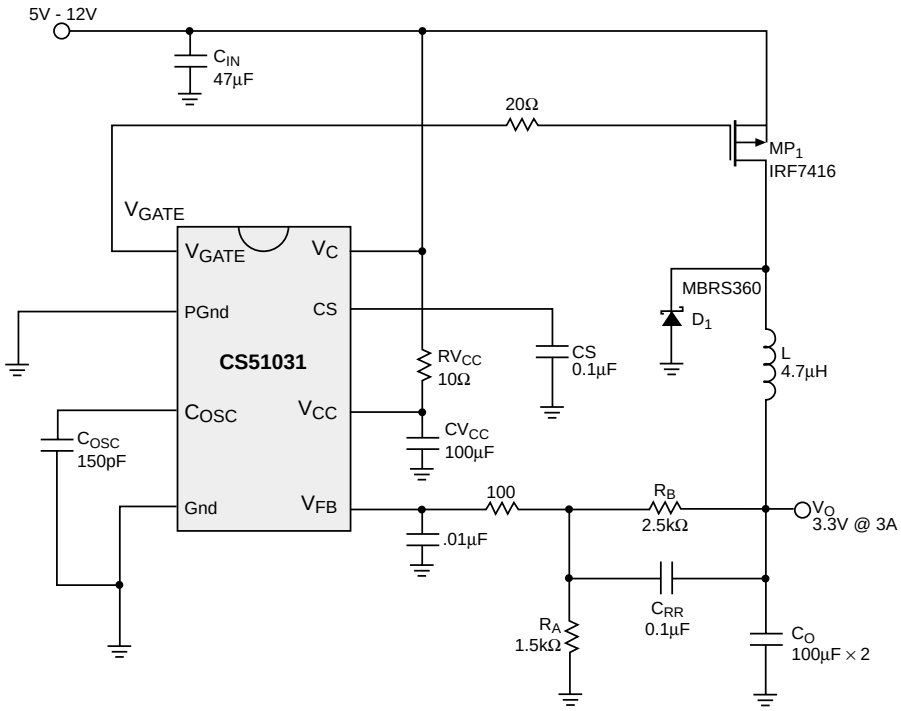
The high frequency oscillator allows the use of small inductors and output capacitors, minimizing PC board area and systems cost. The programmable soft start reduces current surges at start up. The short circuit protection timer significantly reduces the duty cycle to approximately 1/30 of its cycle during short circuit conditions.

The CS51031 is available in 8 Lead SO and 8 Lead PDIP plastic packages.

## Features

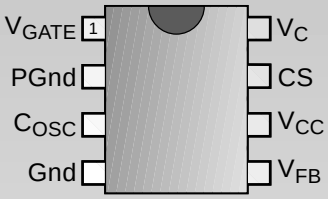
- **1A Totem Pole Output Driver**
- **High Speed Oscillator (700kHz max)**
- **No Stability Compensation Required**
- **Lossless Short Circuit Protection**
- **$V_{CC}$ Monitor**
- **2% Precision Reference**
- **Programmable Soft Start**
- **Wide Ambient Temperature Range:**
  **Industrial Grade: –40°C to 85°C**
  **Commercial Grade: 0°C to 70°C**

## Typical Application Diagram




## Package Options

**8 Lead SO Narrow & PDIP**




ON Semiconductor
2000 South County Trail, East Greenwich, RI 02818
Tel: (401)885–3600 Fax: (401)885–5786
N. American Technical Support: 800-282-9855
Web Site: www.cherry–semi.com

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## Absolute Maximum Ratings

Power Supply Voltage, $V_{CC}$ ..... 20V
Driver Supply Voltage, $V_C$ ..... 20V
Driver Output Voltage, $V_{GATE}$ ..... 20V
$C_{OSC}$, CS, $V_{FB}$ (Logic Pins) ..... 6V
Peak Output Current ..... 1.0A
Steady State Output Current ..... 200mA
Operating Junction Temperature, $T_J$ ..... 150°C
Operating Temperature Range, $T_A$ ..... -40° to 85°C
Storage Temperature Range, $T_S$ ..... -65 to 150°C
ESD (Human Body Model) ..... 2kV
Lead Temperature Soldering
Wave Solder (through hole styles only) ..... 10 sec. max, 260°C peak
Reflow (SMD styles only) ..... 60 sec. max above 183°C, 230°C peak

**Electrical Characteristics: Specifications apply for $4.5 \le V_{CC} \le 16V$, $3V \le V_C \le 16V$; Industrial Grade: $-40°C < T_A < 85°C$; $-40°C < T_J < 125°C$: Commercial Grade: $0°C < T_A < 70°C$; $0°C < T_J < 125°C$, unless otherwise specified.**

| PARAMETER | TEST CONDITIONS | MIN | TYP | MAX | UNIT |
|---|---|---|---|---|---|
| **■ Oscillator** | **$V_{FB}$ = 1.2V** | | | | |
| Frequency | $C_{OSC}$ = 470pF | 160 | 200 | 240 | kHz |
| Charge Current | $1.4V < V_{COSC} < 2V$ | | 110 | | µA |
| Discharge Current | $2.7V > V_{COSC} > 2V$ | | 660 | | µA |
| Maximum Duty Cycle | $1 - (t_{OFF} / t_{ON})$ | 80.0 | 83.3 | | % |
| **■ Short Circuit Timer** | **$V_{FB}$ = 1.0V; CS = 0.1µF; $V_{COSC}$ = 2V** | | | | |
| Charge Current | $1V < V_{CS} < 2V$ | 175 | 264 | 325 | µA |
| Fast Discharge Current | $2.55V > V_{CS} > 2.4V$ | 40 | 66 | 80 | µA |
| Slow Discharge Current | $2.4V > V_{CS} > 1.5V$ | 4 | 6 | 10 | µA |
| Start Fault Inhibit Time | $0V < V_{CS} < 2.5V$ | 0.70 | 0.85 | 1.40 | ms |
| Valid Fault Time | $2.6V > V_{CS} > 2.4V$ | 0.2 | 0.3 | 0.45 | ms |
| GATE Inhibit Time | $2.4V > V_{CS} > 1.5V$ | 9 | 15 | 23 | ms |
| Fault Duty Cycle | | 2.5 | 3.1 | 4.6 | % |
| **■ CS Comparator** | **$V_{FB}$ = 1V** | | | | |
| Fault Enable CS Voltage | | | 2.5 | | V |
| Max. CS Voltage | $V_{FB}$ = 1.5V | | 2.6 | | V |
| Fault Detect Voltage | $V_{CS}$ when GATE goes high | | 2.4 | | V |
| Fault Inhibit Voltage | Minimum $V_{CS}$ | | 1.5 | | V |
| Hold Off Release Voltage | $V_{FB}$ = 0V | 0.4 | 0.7 | 1.0 | V |
| Regulator Threshold Voltage Clamp | $V_{CS}$ = 1.5V | 0.725 | 0.866 | 1.035 | V |
| **■ $V_{FB}$ Comparators** | **$V_{COSC} = V_{CS}$ = 2V** | | | | |
| Regulator Threshold Voltage | $T_J$ = 25°C (note 1)<br>$T_J$ = -40 to 125°C | 1.225<br>1.210 | 1.250<br>1.250 | 1.275<br>1.290 | V<br>V |
| Fault Threshold Voltage | $T_J$ = 25°C (note 1)<br>$T_J$ = -40 to 125°C | 1.12<br>1.10 | 1.15<br>1.15 | 1.17<br>1.19 | V<br>V |
| Threshold Line Regulation | $4.5V \le V_{CC} \le 16V$ | | 6 | 15 | mV |
| Input Bias Current | $V_{FB}$ = 0V | | 1 | 4 | µA |
| Voltage Tracking | (Regulator Threshold Voltage - Fault Threshold Voltage) | 70 | 100 | 120 | mV |
| Input Hysteresis Voltage | | | 4 | 20 | mV |

**Electrical Characteristics: Specifications apply for $4.5 \le V_{CC} \le 16V$, $3V \le V_C \le 16V$; Industrial Grade: $-40°C < T_A < 85°C$; $-40°C < T_J < 125°C$: Commercial Grade: $0°C < T_A < 70°C$; $0°C < T_J < 125°C$, unless otherwise specified.**

| PARAMETER | TEST CONDITIONS | MIN | TYP | MAX | UNIT |
|---|---|---|---|---|---|
| **■ Power Stage** | **$V_{CC} = V_C = 10V$; $V_{FB} = 1.2V$** | | | | |
| GATE DC Low Saturation Voltage | $V_{COSC} = 1V$; 200mA Sink | | 1.2 | 1.5 | V |
| GATE DC High Saturation Voltage | $V_{COSC} = 2.7V$; 200mA Source; $V_C = V_{GATE}$ | | 1.5 | 2.1 | V |
| Rise Time | $C_{GATE} = 1nF$; $1.5V < V_{GATE} < 9V$ | | 25 | 60 | ns |
| Fall Time | $C_{GATE} = 1nF$; $9V > V_{GATE} > 1.5V$ | | 25 | 60 | ns |
| **■ $V_{CC}$ Monitor** | | | | | |
| Turn On Threshold | | 4.200 | 4.400 | 4.600 | V |
| Turn Off Threshold | | 4.085 | 4.300 | 4.515 | V |
| Hysteresis | | 65 | 130 | 200 | mV |
| **■ Current Drain** | | | | | |
| $I_{CC}$ | $4.5V < V_{CC} < 16V$, Gate switching | | 4.5 | 6.0 | mA |
| $I_C$ | $3V < V_C < 16V$, Gate non-switching | | 2.7 | 4.0 | mA |
| Shutdown $I_{CC}$ | $V_{CC} = 4$, | | 500 | 900 | µA |

Note 1: Guaranteed by design not 100% tested in production.

**Package Pin Description**

| PACKAGE PIN # | PIN SYMBOL | FUNCTION |
|---|---|---|
| **8 Lead SO Narrow & PDIP** | | |
| 1 | $V_{GATE}$ | Driver pin to gate of external PFET. |
| 2 | PGnd | Output power stage ground connection. |
| 3 | $C_{OSC}$ | Oscillator frequency programming capacitor. |
| 4 | Gnd | Logic ground. |
| 5 | $V_{FB}$ | Feedback voltage input. |
| 6 | $V_{CC}$ | Logic supply voltage. |
| 7 | CS | Soft start and fault timing capacitor. |
| 8 | $V_C$ | Driver supply voltage. |

## Block Diagram

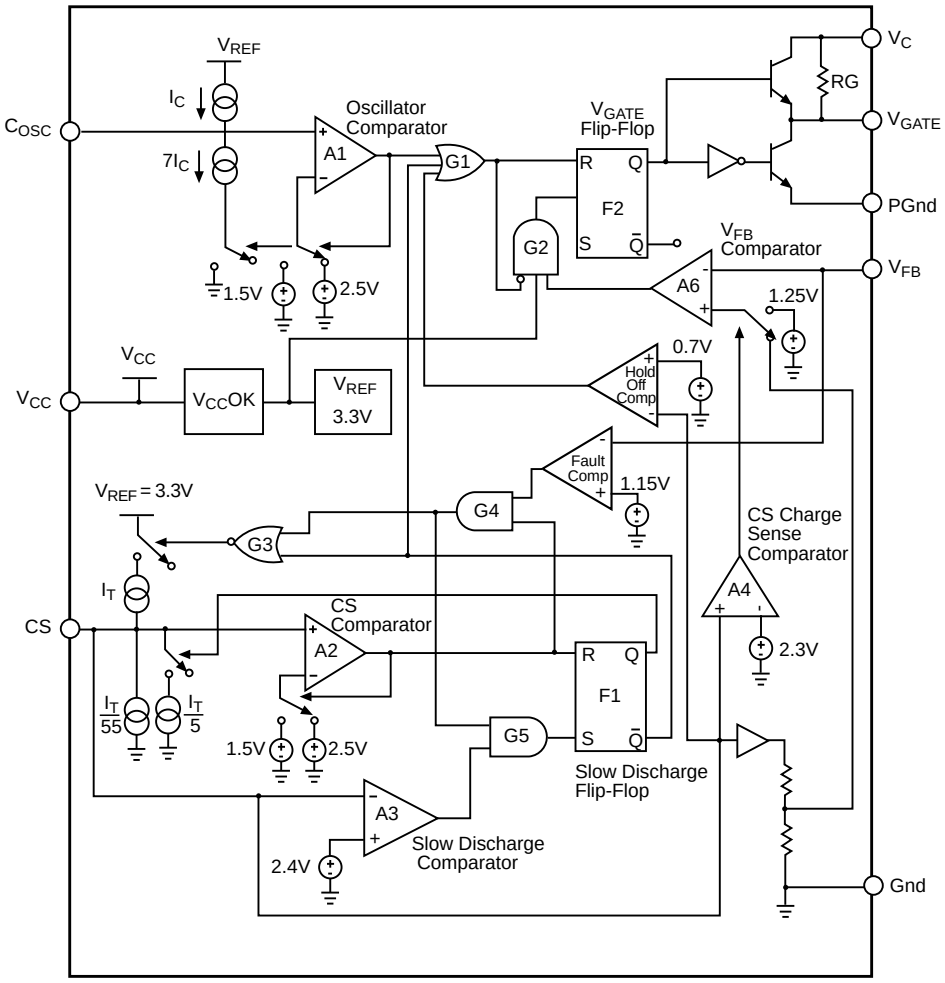



**Figure 1: Block Diagram for CS51031**

## Circuit Description

### Theory of Operation

#### Control Scheme

The CS51031 monitors and the output voltage to determine when to turn on the PFET. If $V_{FB}$ falls below the internal reference voltage of 1.25V during the oscillator's charge cycle, the PFET is turned on and remains on for the duration of the charge time. The PFET gets turned off and remains off during the oscillator's discharge time with the maximum duty cycle to 80%. It requires 7mV typical, and 20mV maximum ripple on the $V_{FB}$ pin is required to operate. This method of control does not require any loop stability compensation.

#### Startup

The CS51031 has an externally programmable soft start feature that allows the output voltage to come up slowly, preventing voltage overshoot on the output.

At startup, the voltage on all pins is zero. As $V_{CC}$ rises, the $V_C$ voltage along with the internal resistor $R_G$ keeps the PFET off. As $V_{CC}$ and $V_C$ continue to rise, the oscillator capacitor ($C_{OSC}$ ) and the Soft Start / Fault Timing capacitor (CS) charges via internal current sources. $C_{OSC}$ gets charged by the current source $I_C$ and CS gets charged by the $I_T$ source combination described by:

$$I_{CS} = I_T - \left( \frac{I_T}{55} + \frac{I_T}{5} \right).$$

The internal Holdoff Comparator ensures that the external PFET is off until $V_{CS} > 0.7V$, preventing the GATE flip-flop (F2) from being set. This allows the oscillator to reach its operating frequency before enabling the drive output. Soft start is obtained by clamping the $V_{FB}$ comparator's (A6) reference input to approximately 1/2 of the voltage at the CS pin during startup, permitting the control loop and the output voltage to slowly increase. Once the CS pin charges above the Holdoff Comparator trip point of 0.7V, the low feedback to the $V_{FB}$ Comparator sets the GATE flip-flop during $C_{OSC}$ 's charge cycle. Once the GATE flip-flop is set, $V_{GATE}$ goes low and turns on the PFET. When $V_{CS}$ exceeds

2.4V, the CS charge sense comparator (A4) sets the $V_{FB}$ comparator reference to 1.25V completing the startup cycle.

### Lossless Short Circuit Protection

The CS51031 has “lossless” short circuit protection since there is no current sense resistor required. When the voltage at the CS pin (the fault timing capacitor voltage ) reaches 2.5V during startup, the fault timing circuitry is enabled. During normal operation the CS voltage is 2.6V. During a short circuit or a transient condition, the output voltage moves lower and the voltage at $V_{FB}$ drops. If $V_{FB}$ drops below 1.15V, the output of the fault comparator goes high and the CS51031 goes into a fast discharge mode. The fault timing capacitor, CS, discharges to 2.4V. If the $V_{FB}$ voltage is still below 1.15V when the CS pin reaches 2.4V, a valid fault condition has been detected. The slow discharge comparator output goes high and enables gate G5 which sets the slow discharge flip flop. The Vgate flip flop resets and the output switch is turned off. The fault timing capacitor is slowly discharged to 1.5V. The CS51031 then enters a normal startup routine. If the fault is still present when the fault timing capacitor voltage reaches 2.5V, the fast and slow discharge cycles repeat as shown in figure 2.

If the $V_{FB}$ voltage is above 1.15V when CS reaches 2.4V a fault condition is not detected, normal operation resumes and CS charges back to 2.6V. This reduces the chance of erroneously detecting a load transient as a fault condition.

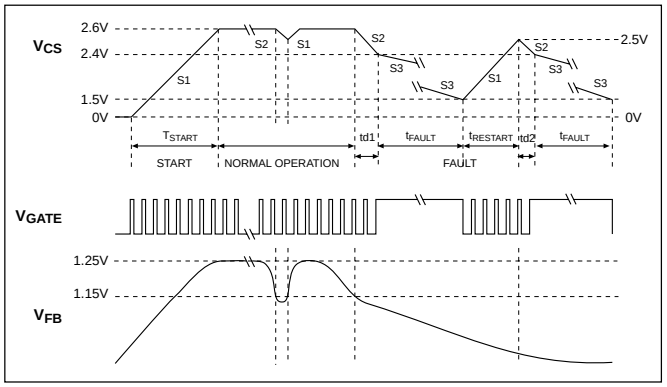



**Figure 2. Voltage on start capacitor ($V_{GS}$ ), the gate ($V_{GATE}$ ), and in the feedback loop ($V_{FB}$), during startup, normal and fault conditions.**

### Buck Regulator Operation

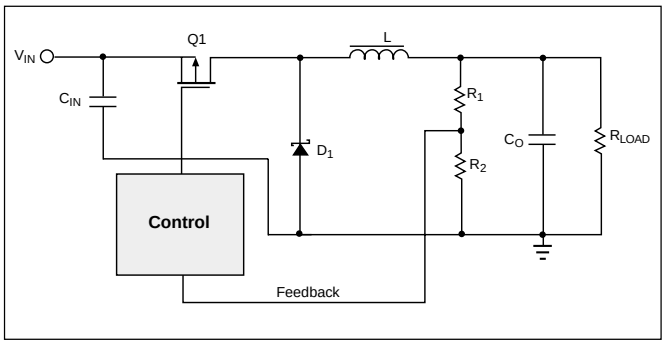



**Figure 3. Buck regulator block diagram.**

A block diagram of a typical buck regulator is shown in Figure 3. If we assume that the output transistor is initially off, and the system is in discontinuous operation, the inductor current $I_L$ is zero and the output voltage is at its nominal value. The current drawn by the load is supplied by the output capacitor $C_O$. When the voltage across $C_O$ drops below the threshold established by the feedback resistors R1 and R2 and the reference voltage $V_{REF}$, the power transistor Q1 switches on and current flows through the inductor to the output. The inductor current rises at a rate determined by $(V_{IN}-V_{OUT})/L$. The duty cycle (or “on” time) for the CS51031 is limited to 80%. If output voltage remains higher than nominal during the entire $C_{OSC}$ change time, the Q1 does not turn on, skipping the pulse.

## Applications Information

### CS51031 Design Example

**Specifications 12V to 5V, 3A Buck converter**

$V_{IN}$ = 12V ±20% (i.e. 14.4V max., 12Vnom., 9.6V min.)

$V_{OUT}$ = 5V ±2%

$I_{OUT}$ = 0.3A to 3A

Output ripple voltage < 50mV max.

Efficiency > 80%

$f_{SW}$ = 200kHz

### 1) Duty cycle estimates

Since the maximum duty cycle D, of the CS51031 is limited to 80% min., it is necessary to estimate the duty cycle for the various input conditions over the complete operating range.

The duty cycle for a buck regulator operating in a continuous conduction mode is given by:

$$D = \frac{V_{OUT} + V_F}{V_{IN} - V_{SAT}}$$

## Applications Information: continued

where $V_{SAT} = R_{ds(on)} \times I_{OUT}$ max. and $R_{ds(on)}$is the value at $T_J$ 100°C.

If $V_F$ = 0.60V and $V_{SAT}$ = 0.60V then the above equation becomes:

$$D_{MAX} = \frac{5.6}{9} = 0.62$$

$$D_{MIN} = \frac{5.6}{13.8} = 0.40$$

**2) Switching frequency and on and off time calculations**

Given that $f_{SW}$ = 200kHz and $D_{MAX}$ = 0.80

$$T = \frac{1}{f_{SW}} = 5\mu s$$

$$T_{ON(max)} = T \times D_{MAX} = 5\mu s \times 0.62 \cong 3\mu s$$

$$T_{ON(min)} = T \times D_{MIN} = 5\mu s \times 0.40 = 2\mu s$$

$$T_{OFF(max)} = T_{ON(min)} = 5\mu s - 2\mu s = 3\mu s$$

**3) Oscillator Capacitor Selection**

The switching frequency is set by $C_{OSC}$, whose value is given by:

$$C_{OSC} \text{ in pF} = \frac{95 \times 10^{-6}}{F_{sw}\left(1 + \frac{F_{sw}}{3 \times 10^6} - \left(\frac{30 \times 10^3}{F_{sw}}\right)^2\right)}$$

**4) Inductor selection**

The inductor value is chosen for continuous mode operation down to 0.3Amps.

The ripple current $\Delta I = 2 \times I_{OUT}\text{min} = 2 \times 0.3A = 0.6A$.

$$L_{min} = \frac{(V_{OUT} + V_D) \times T_{OFF(max)}}{\Delta I} = \frac{5.6V \times 3\mu s}{0.6A} = 28\mu H$$

This is the minimum value of inductor to keep the ripple current to < 0.6A during normal operation.

A smaller inductor will result in larger ripple current. Ripple current at a minimum off time is

$$\Delta I = \frac{(V_{OUT} + V_F) \times T_{OFF(min)}}{L_{MIN}} = \frac{5.6V \times 2\mu s}{28\mu H} = 0.4A$$

The core must not saturate with the maximum expected current, here given by:

$$I_{MAX} = I_{OUT} + \Delta I / 2 = 3A + 0.4A / 2 = 3.2A$$

**5) Output capacitor**

The output capacitor and the inductor form a low pass filter. The output capacitor should have a low ESL and ESR. Low impedance aluminum electrolytic, tantalum or organic semiconductor capacitors are a good choice for an output capacitor. Low impedance aluminum are less expensive. Solid tantalum chip capacitors are available from a number of suppliers and are the best choice for surface mount applications.

The output capacitor limits the output ripple voltage. The CS51031 needs a maximum of 20mV of output ripple for the feedback comparator to change state. If we assume that all the inductor ripple current flows through the output capacitor and that it is an ideal capacitor (i.e. zero ESR), the minimum capacitance needed to limit the output ripple to 50mV peak to peak is given by:

$$C = \frac{\Delta I}{8 \times f_{SW} \times \Delta V} = \frac{0.6A}{8 \times (200 \times 10^3 Hz) \times (50 \times 10^{-3} V)} = 7.5\mu F$$

The minimum ESR needed to limit the output voltage ripple to 50mV peak to peak is:

$$ESR = \frac{\Delta V}{\Delta I} = \frac{50 \times 10^{-3}}{0.6A} = 83m\Omega$$

The output capacitor should be chosen so that its ESR is less than 83mΩ.

During the minimum off time, the ripple current is 0.4A and the output voltage ripple will be:

$$\Delta V = ESR \times \Delta I = 83m\Omega \times 0.4 = 33mV.$$

**6) $V_{FB}$ divider**

$$V_{OUT} = 1.25V\left(\frac{R1 + R2}{R2}\right) = 1.25V\left(\frac{R1}{R2} + 1\right)$$

The input bias current to the comparator is 4µA. The resistor divider current should be considerably higher than this to ensure that there is sufficient bias current. If we choose the divider current to be at least 250 times the bias current this permits a divider current of 1mA and simplifies the calculations.

$$\frac{5V}{1mA} = R1 + R2 = 5k\Omega$$

Let R2 = 1K

Rearranging the divider equation gives:

$$R1 = R2\left(\frac{V_{OUT}}{1.25} - 1\right) = 1k\Omega\left(\frac{5V}{1.25} - 1\right) = 3k\Omega$$

**7) Divider bypass Capacitor Crr**

Since the feedback resistors divide the output voltage by a factor of 4, i.e. 5V / 1.25V= 4, it follows that the output ripple is also divided by four. This would require that the output ripple be at least 60mV (4 × 15mV) to trip the feedback comparator. We use a capacitor Crr to act as an AC short .

The ripple voltage frequency is equal to the switching frequency so we choose Crr = 1nF.

**8) Soft start and Fault timing capacitor CS.**

CS performs several important functions. First it provides a delay time for load transients so that the IC does not enter a fault mode every time the load changes abruptly. Secondly it disables the fault circuitry during startup, it also provides soft start by clamping the reference voltage during startup, allowing it to rise slowly, and, finally it controls the hiccup short circuit protection circuitry. This reduces the duty cycle to approximately 0.035 during short circuit conditions.

An important consideration in calculating CS is that it's voltage does not reach 2.5V (the voltage at which the fault detect circuitry is enabled) before $V_{FB}$ reaches 1.15V otherwise the power supply will never start.

If the $V_{FB}$ pin reaches 1.15V, the fault timing comparator will discharge $C_S$ and the supply will not start. For the $V_{FB}$ voltage to reach 1.15V the output voltage must be at least $4 \times 1.15 = 4.6V$.

If we choose an arbitrary startup time of 900µs, the value of $C_S$ is:

$$t_{Startup} = \frac{C_S \times 2.5V}{I_{Charge}}$$

$$C_S min = \frac{900\mu s \times 264\mu A}{2.5V} = 950nF \cong 0.1\mu F$$

The fault time is the sum of the slow discharge time the fast discharge time and the recharge time. It is dominated by the slow discharge time.

The first parameter is the slow discharge time, it is the time for the $C_S$ capacitor to discharge from 2.4V to 1.5V and is given by:

$$t_{SlowDischarge(t)} = \frac{C_S \times (2.4V - 1.5V)}{I_{Discharge}}$$

Where $I_{Discharge}$ is 6µA typical.

$$t_{SlowDischarge(t)} = C_S \times 1.5 \times 10^5$$

The fast discharge time occurs when a fault is first detected. The $C_S$ capacitor is discharged from 2.5V to 2.4V.

$$t_{FastDischarge(t)} = \frac{C_S \times (2.5V - 2.4V)}{I_{FastDischarge}}$$

Where $I_{FastDischarge}$ is 66µA typical.

$$t_{FastDischarge(t)} = C_S \times 1515$$

The recharge time is the time for $C_S$ to charge from 1.5V to 2.5V.

$$t_{Charge(t)} = \frac{C_S \times (2.5V - 1.5V)}{I_{Charge}}$$

Where $I_{Charge}$ is 264µA typical.

$$t_{Charge(t)} = C_S \times 3787$$

The fault time is given by:

$$t_{Fault} = C_S \times (3787 + 1515 + 1.5 \times 10^5)$$

$$t_{Fault} = C_S \times (1.55 \times 10^5)$$

For this circuit

$$t_{Fault} = 0.1 \times 10^{-6} \times 1.55 \times 10^5 = 15.5\mu S$$

A larger value of $C_S$ will increase the fault time out time but will also increase the soft start time.

**9) Input Capacitor**

The input capacitor reduces the peak currents drawn from the input supply and reduces the noise and ripple voltage on the $V_{CC}$ and $V_C$ pins. This capacitor must also ensure that the $V_{CC}$ remains above the UVLO voltage in the event of an output short circuit. A low ESR capacitor of at least 100µF is good. A ceramic surface mount capacitor should also be connected between $V_{CC}$ and ground to filter high frequency noise.

**10) MOSFET Selection**

The CS51031 drives a P-channel MOSFET. The $V_{GATE}$ pin swings from Gnd to $V_C$. The type of PFET used depends on the operating conditions but for input voltages below 7V a logic level FET should be used.

A PFET with a continuous drain current ($I_D$) rating greater than the maximum output current is required.

The Gate-to-Source voltage $V_{GS}$ and the Drain-to Source Breakdown Voltage should be chosen based on the input supply voltage.

The power dissipation due to the conduction losses is given by:

$$P_D = I_{OUT}^2 \times R_{DS(ON)} \times D \text{ where}$$

$R_{DS(ON)}$ is the value at $T_J = 100°C$.

The power dissipation of the PFET due to the switching losses is given by:

$$P_D = 0.5 \times V_{IN} \times I_{OUT} \times (t_r) \times f_{SW}$$

Where $t_r$ = Rise Time.

**11) Diode Selection**

The flyback or catch diode should be a Schottky diode because of it's fast switching ability and low forward voltage drop. The current rating must be at least equal to the maximum output current. The breakdown voltage should be at least 20V for this 12V application.

The diode power dissipation is given by:

$$P_D = I_{OUT} \times V_D \times (1 - D_{min})$$

## Package Specification

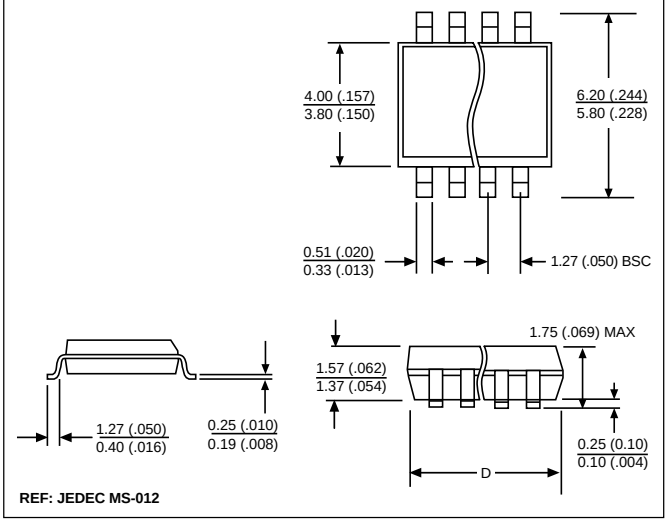
### PACKAGE DIMENSIONS IN mm (INCHES)

| Lead Count | D | | | |
|---|---|---|---|---|
| | Metric | | English | |
| | Max | Min | Max | Min |
| 8 Lead SO Narrow | 5.00 | 4.80 | .197 | .189 |
| 8 Lead PDIP | 10.16 | 9.02 | .400 | .355 |

### PACKAGE THERMAL DATA

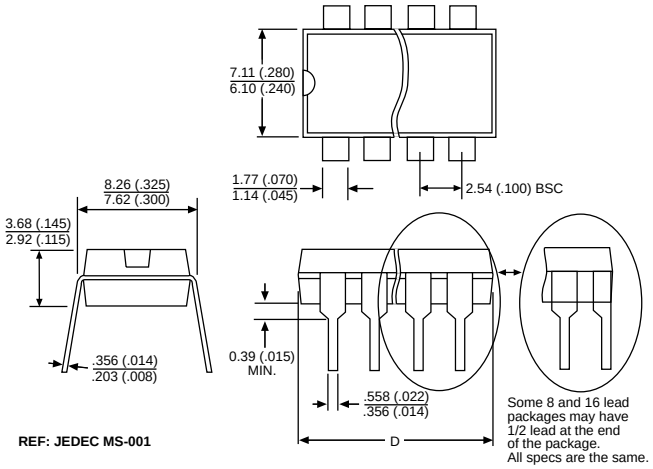
| Thermal Data | | 8L SO Narrow | 8L PDIP | |
|---|---|---|---|---|
| $R_{\Theta JC}$ | typ | 45 | 52 | °C / W |
| $R_{\Theta JA}$ | typ | 165 | 100 | °C / W |

### 8 Lead Surface Mount Narrow Body (D); 150 mil wide




REF: JEDEC MS-012

### 8 Lead Plastic DIP (N); 300 mil wide




REF: JEDEC MS-001

### Ordering Information

| Part Number | Temperature Range | Description |
|---|---|---|
| CS51031ED8 | –40° < $T_A$ < 85°C | 8 Lead SO Narrow |
| CS51031EDR8 | –40° < $T_A$ < 85°C | 8 Lead SO Narrow *(tape & reel)* |
| CS51031EN8 | –40° < $T_A$ < 85°C | 8 Lead PDIP |
| CS51031GD8 | 0° < $T_A$ < 70°C | 8 Lead SO Narrow |
| CS51031GDR8 | 0° < $T_A$ < 70°C | 8 Lead SO Narrow *(tape & reel)* |
| CS51031GN8 | 0° < $T_A$ < 70°C | 8 Lead PDIP |