The MOD12003 is a standard-precision, 20 V, 3 A module for the MOD1 series of multi-output, modular power supplies. It uses a hybrid switching + linear architecture that achieves acceptable noise levels for most uses while also maintaining low power dissipation.

Table 1: Specifications

Parameter	Value	Unit
Voltage		
Full-scale output voltage	20	V
Output voltage resolution	10	mV
Output voltage tolerance	$0.5\% \pm 10$	mV
Minimum output-enabled voltage	100	mV
Current		
Full-scale output current	3	A
Output current resolution	2	mA
Output current tolerance	$0.5\% \pm 2$	mA
Min. current limit, worst case	10	mA
Current sense dead zone, worst case	0 – 10	mA
Slew rate (software programmable)		
Max. rising slew rate (allow 2% + 15 mV overshoot)	3.2	V/ms
Max. rising slew rate (no overshoot)	2.0	V/ms
Falling slew time constant (first-order RC)	200	ms
Overload		
Max. forced pos. output voltage (passive)	24	V
Max. forced pos. output voltage (fuse blows)	63	V
Max. forced neg. output voltage (passive)	-0.3	V
Max. forced neg. output voltage (fuse blows)	-63	V
Fuse rupture capacity	50	A
On-board spare fuses (install with solder bridge)	2	
Programmable OVP (blows fuse if necessary)	3 – 24	V
OVP threshold resolution	150	mV
OVP threshold tolerance	$2\% \pm 50$	mV

Contents

List of Figures

List of Tables

Chapter 1

Theory of Operation

1.1 Introduction

This chapter describes the operation of the MOD12003 , ranging from a broad overview to detailed sections on subcircuits and software routines.

Block Diagram

Figure 1.1 contains a block diagram of the MOD12003 .

The MOD12003 uses a standard, high-side regulation architecture. A 24 V input passes through an input protection block (including reverse polarity blocking and inrush current limiting / bulk capacitance isolation) and directly into a software-controlled buck converter. The output of this converter then passes through a linear regulator stage and to the output. The output voltage is sensed directly at the output connector and passes back to both the linear regulator and the microcontroller.

The output is fused, protecting internal circuitry in the event that power is applied to the outputs externally, and helping to minimize damage to both the MOD12003 and to the device to which power is being supplied if the MOD12003 fails.

The standard MOD1 serial loop interface feeds a capacitive coupler and is processed directly by the microcontroller; passthrough to downstream modules is also handled in software.

1.2 Detailed Description

Microcontroller

The Microcontroller is the device in control of the entire system. It receives signals from the MOD1 motherboard, storing the desired output voltage, current, and slew rate. These, combined with stored calibration data, are used to choose setpoints for both the Preregulator and the Linear Regulator. Status signals from these circuits, including the output voltage and current, regulation mode, and heat sink temperature, are monitored. These all provide feedback for multiple safety and limiting functions.

Calibration

There are two major sources of error that must be corrected; calibration accounts for the first one. This is manufacturing tolerance in the voltage sense and current sense amplifiers and in the system voltage reference, which could cause the supply to read its own outputs incorrectly and deliver an erroneous level.

To perform adjustment, the Microcontroller configures the regulators for four test points: approximately 10% and 90% of full scale for both current and voltage. These initial setpoints need not be correct. After they have stabilized, both the Microcontroller and a human operator individually measure the actually achieved value, and the operator-supplied measurement is entered into the system. These points are used to apply a linear correction to the data read by the Analog-Digital Converter.

Voltage Control Loop

The second major source of error is inaccuracy and drift in the Linear Regulator. The error amplifiers in this are not required to be accurate initially or in the long term. As such, they may have significant offset voltage, and this offset voltage may change significantly over temperature variants and time.

This error is removed by a self-correcting control loop implemented in the Microcontroller. The Analog-Digital Converter digitizes the signals from the Sense Amplifiers, and calibration is applied. The corrected value of the output voltage is compared to the desired output voltage, and this error serves as the input to a control loop that corrects the error.

Because this error source is slow, this control loop is designed to be slow and gentle to avoid loop stability interactions between it and the tighter, faster loops of the Linear Regulator.

The use of such a correcting loop is a decision that was made to reduce complexity and expense in the hardware of the Linear Regulator. Because the required connections and peripherals in the Microcon-

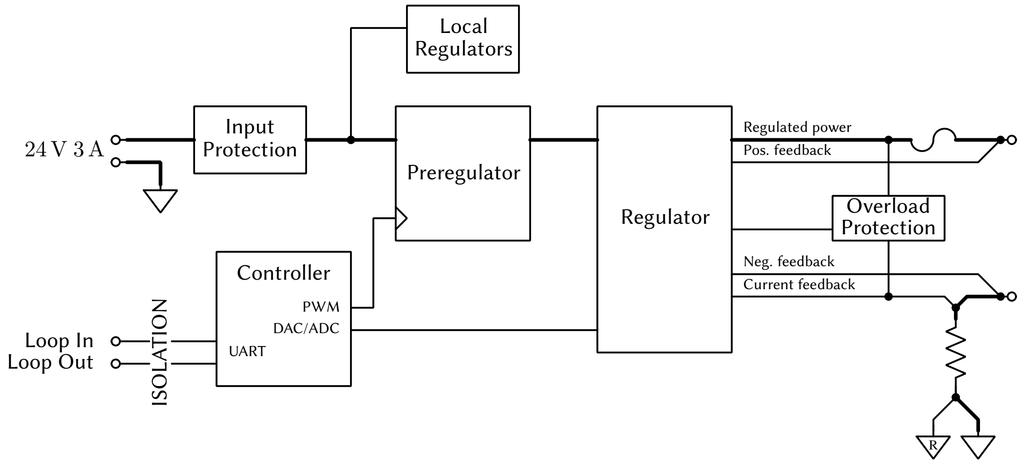

Figure 1.1: Block diagram

troller were already in use, the Voltage Control Loop could be added at the cost of only a few lines of firmware code, allowing the error amplifier in the Linear Regulator to consist of only two very modest operational amplifiers.

Overvoltage Protection

The MOD12003 's overvoltage protection is a system involving two control methods. At its heart is a thyristor connected across the supply outputs. Current supplied to the thyristor's gate bias circuit will cause it to latch closed-circuit, conducting current until the output fuse opens.

A comparator is constantly comparing the output voltage, as read by the Sense Amplifier, to a reference signal. This reference signal is supplied by the Microcontroller as a pulse width modulated (PWM) waveform and filtered to produce a fixed level. If at any moment the output voltage exceeds this point, the comparator alternates, saturating a transistor that drives the thyristor's gate into conduction.

Due to the inaccurate nature of the PWM-derived level, this analog method is only used for fast reponse and as a last resort if the Microcontroller stops functioning [1]. More accurate protection is provided by the Microcontroller firmware. If the output voltage is detected beyond a narrow margin above the setpoint, the PWM signal will saturate, quickly forcing the thyristor into conduction regardless of the output voltage as seen by the comparator.

Group Error Response

In an environment where multiple supply modules are used to power multiple rails of a single device, it may be desirable to have so-called Group Error Response. The Microcontroller detects multiple error conditions, including overvoltage protection trip, output current exceeding a set value (if desired, with a fixed grace period to allow inrush currents), thermal overload, and oscillation of the Linear Regulator. If Group Error Response is configured, the selected error conditions will cause the Microcontroller to notify all the other modules in the MOD1 system, prompting the entire system to shut down as a precaution.

Preregulator

To allow substantial amounts of power to be delivered by a relatively small supply module, a relatively high-efficiency buck-mode DC-DC converter is employed. This is controlled by a pulse-width modulated waveform from the Microcontroller. An amplifier translates and shifts the signal to provide a 0 V to −14 V (relative to the positive supply) gate drive waveform to a power P-channel MOSFET. The MOSFET, in conjunction with a Schottky diode, chops the supply into a square wave which is then filtered by an LC filter circuit.

Software control allows the Preregulator to be controlled in a way that is most suitable for a hybrid power supply. Under higher power conditions, the voltage drop across the Linear Regulator will be minimized to keep its temperature low. Only a small amount of voltage 'headroom' is required to maintain an acceptable transient response. However, this is not optimal under lower power conditions. The regulator would switch into 'discontinuous' mode, meaning that the MOSFET and diode are not always conducting. There is a dead time during which output current is supplied only by the filter capacitors. This increases output voltage ripple and high-frequency noise (the latter due to the ringing that is usually present in the system when the normally driven 'switching node' becomes a high impedance). When the output power level is low enough for this to happen, it will also be low enough

[1] The PWM signal is generated by a relatively isolated peripheral inside the Microcontroller, which is expected to continue operation in the event of software errors or freezes.

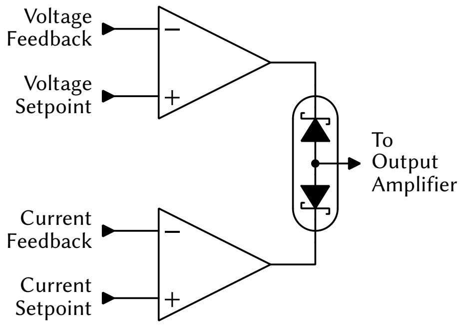

Figure 1.2: Linear regulator partial: control amplifier

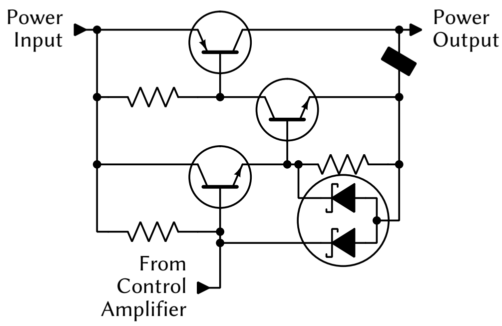

Figure 1.3: Linear regulator partial: output amplifier

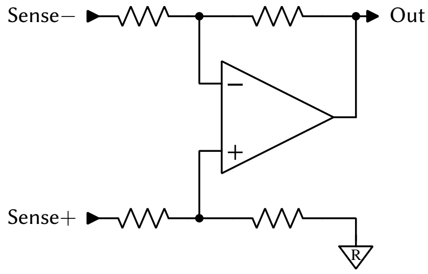

Figure 1.4: Voltage sense amplifier

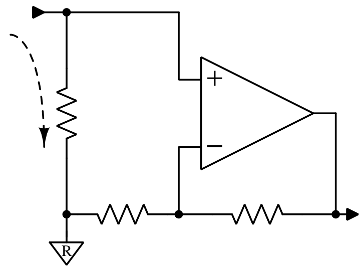

Figure 1.5: Current sense amplifier

for the Linear Regulator to provide all regulation by itself, and so the Microcontroller will simply switch the MOSFET 'on' and allow the full input voltage to reach the Linear Regulator.

Linear Regulator

Despite the efficiency benefit of the buck converter, it is not ideal. A switching converter's output has a large amount of voltage ripple and it does not have a particularly nice transient response. To convert the output of the Preregulator into a sufficiently clean supply, a Linear Regulator passes and regulates the supply.

Control Amplifiers

Figure 1.2 shows a simplified, partial schematic of the control amplifier. Operational amplifier `U2B` compares the voltage setpoint to the voltage feedback, driving the output amplifier through switching diode pair `D3`. Likewise, operational amplifier `U2A` compares the current setpoint to the current feedback, also driving the output amplifier through `D3`. The switching diode pair ensures that the output amplifier is driven by whichever of the two control amplifiers is producing the smaller signal, allowing either amplifier to 'limit' the other.

Output Amplifier

Figure 1.3 shows a simplified schematic of the output amplifier. `Q10` and `Q12` form a complementary feedback pair to supply the output current, and two ferrite beads stabilize the pair against layout-induced oscillation. `Q11` buffers the output signal further to ensure that even when manufacturing variations give low current gain in the `Q10`, a relatively high resistor can supply the bias to the output amplifier.

Diode pair `D4` protects the emitter-base junctions of `Q11` and `Q12` in the case that the output voltage is externally forced above the setpoint.

Sense Amplifiers

Figure 1.4 shows a simplified schematic of the voltage sense amplifier. This is a differential amplifier that translates the output voltage, as detected between the positive and negative output connectors, onto the system's internal 0 V reference potential. This is multiplied by the gain, which in this case is below unity: $^1/_{11}$. A sub-unity gain allows the relatively large output voltage to be scaled into a range that is acceptable to the Microcontroller's analog-digital and digital-analog converters.

Figure 1.5 shows a simplified schematic of the current sense amplifier. Because the system 0 V reference potential is taken directly at one side of the current sense resistor, differential amplification is not necessary. `U1A` amplifies the voltage across the sense resistor by a fixed gain of 64.2 to maximize the Microcontroller-domain voltage range. A resistor in series with the amplifier's input protects it against voltage spikes that may be present in the event of a sudden output short-circuit.

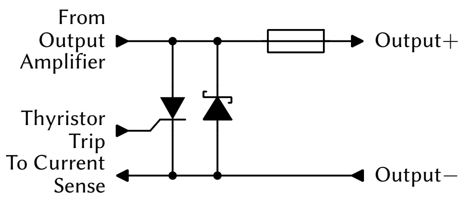

Figure 1.6: Output protection

Output Protection

Both the power supply and the circuit being powered can be protected from each other. A series fuse at the output makes this possible. Thyristor `Q9` and diode `D4` sit behind the fuse (see fig. 1.6) and will blow this fuse under certain conditions

- If a negative voltage is applied to the output, `D4` will conduct.
- If a voltage above 25 V is applied to the output, `DZ1` will trip the thyristor.
- If the output voltage exceeds a software-programmed threshold for any reason, `U5A` via `Q11` will trip the thyristor.
- If the software decides to for any other reason, typically because the output voltage has exceeded the setpoint and cannot be brought down, it will cause `U5A` to trip the thyristor by immediately saturating the trip point.

Thyristors have an internal 'latching' effect that causes them to remain closed-circuit once thy trip until current stops flowing. When `Q9` trips, it will conduct indefinitely or until the fuse blows.

Input Circuit

A small amount of conditioning is applied to the input power. Transistor `Q10A` provides reverse-polarity protection. If power is applied with the polarity reversed, the gate-source voltage applied to `Q10A` will be zero, and it will not switch on. If power is applied with correct polarity, the subtrate diode of the transistor will allow current to flow. As the voltage beyond the transistor rises, the magnitude of the gate-source voltage increases, and eventually the transistor will switch totally 'on' and bypass the substrate diode entirely.

The input current must also pass through `Q10B`, which is inverted with respect to `Q10A` such that it can restrict the flow of *forward* current into the system. As `Q10B` begins to turn on, it must pass through its active region where it controls the output in an analog sense. At this point, it becomes an amplifier, with the drain its output, the source its noninverting input, and the gate its inverting input. Capacitor `C23` provides negative feedback and converts it into an integrator. This gives a linear, controlled, sloping output voltage, which slowly charges the input capacitance of the system rather than allowing a large inrush current to flow. This inrush limiting is essential, as a large inrush current can trip the current limiting feature of some power supplies that might be used as an input source.

Communications