Programmable DC Power Supply Using Linear Regulation

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Note: This document was destroyed for no apparent reason thanks to the magic of computers. As a result, this rewritten form has no pictures and does not contain the code Appendix.

Introduction

Problem:

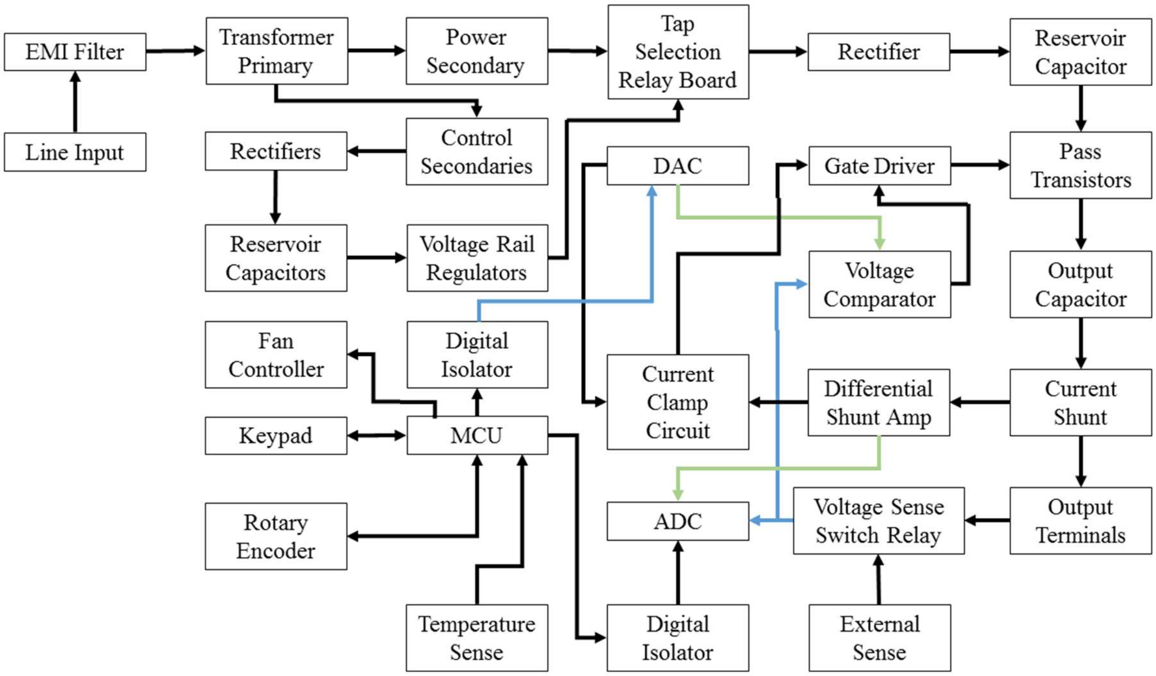
How can a DC power supply be created with low noise, a digitally controlled output, and using the concepts of linear regulation?

Solution:

Creating such a power supply will require a great deal of experimentation to create a linear regulator from off the shelf parts. Because a normal variable voltage regulator will only go to around two amps, a normal IC could never do the job on its own. Additionally, such a voltage regulator cannot output a voltage below its reference voltage (1.25). By using a comparator, an external reference voltage, a precision resistor network, and an optoisolator, a feedback system can be created that forces the output to a certain voltage determined the reference. By using a DAC to produce this external input voltage, digital control can be achieved.

Design

Block Diagram:



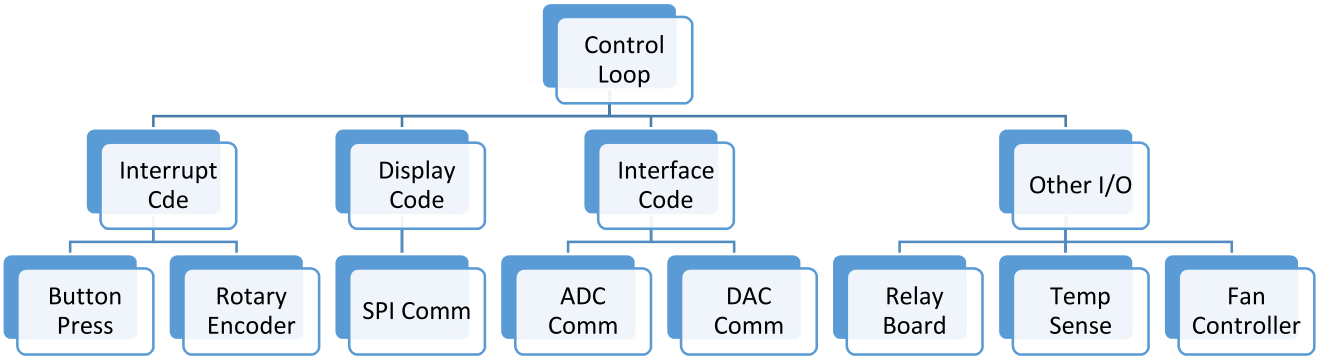
Although this block diagram appears very complicated, it is simply put into very high detail for purposes of explanation of the technology that made the supply operate. Line input denotes the IEC power cord connection which directly feed into the EMI filter. The filter is there to prevent voltage spikes and high frequency noise from entering the supply and to prevent voltage spikes caused during the transformer quench from feeding back into the power line. The line and neutral wires then feed into the isolated primary of the transformer. A multitapped power secondary winding and multiple control circuitry secondaries are wound on the same core for voltage step-down purposes. The power secondary is then fed into a tap selection relay board to pick the voltage to pull off of the transformer to feed into the regulator. The traces on this board where made to be a maximum and there was heavy use of high current via stitching. The relays are rated for 30 amps of continuous current and have sacrifical electrodes built in to prevent inevitable arcing from ruining the relays.

The AC output is put through a high current rectifier constructed of large individual diodes bolted directly to large extruded aluminium heatsinks. The rectified waveform was leveled by being fed into the large 50 mF capacitor. This capacitor was choosen to have this high capacitance to reduce the voltage ripple to one volt when operating with a ten amp load. The reservoir capacitor then feeds into the pass transistors that burn off the excess voltage as heat. Two MOSFETs where used in parallel and with a the same gate driver because these transisitors had temperature coefficients that caused them to conduct less electricity when heated up (the opposite of what NPN transistors normal do). This characteristic of the transistors allows them to self balance the heat load and prevents thermal runaway from taking place.

The output of the pass transistors goes to the relatively small output capacitor. Because the other parts of the control circuitry were designed quite well, a large output capacitor was not needed to give a fairly clean output. The small capacitor is great for allowing near instant changes to the current when in constant current mode. Directly before the terminals was the precision, case-mounted current shunt resistor. The resistance of 1 mOhm was choosen for maximum voltage gain and low heat disipation. At the output terminal is the voltage sense wires that feed back to the sense switch relay. A separate set of terminals is provided for external sense. Two high-quality, shielded reed relays were used on this relay board. The current shunt was connected to a differential shunt amplifier to get a full scale analog output. The voltage sense and amplified current sense where conneceted to a 32-bit ADC for real output to be displayed to the user. The signals were also sent to respective voltage comparator and current clamping circuits that feed into the isolated gate driver. The gate driver provides an analog signal to go into the gates of the MOSFETs.

On the control circuitry route, each of the control secondaries was given it own rectifier, supply capacitor, and TO-220 package voltage regulator to give multiple isolated voltage rails. The microcontroller, a Cortex M4 processor, is the brains of the control circuits. It uses digital isolators to communicate with the DAC and ADC. The DAC is then used to output voltages that set voltage and current limits within those feedback circuits. The microprocessor does not attempt to set the output voltage by reading the output through the ADC and putting out a corresponding signal on the DAC. Regulation takes place completely in the driver and comparator circuitry. The controller also connects to a few temperature sensors mounted to the pass transistors and their heatsink to monitor for excess tempeature. The controller then communicates with the fan controller to set an approprite airflow level in the cooling tunnel. A keypad and rotary encoder are also connected to the processor to allow for convinient and easy user input.

Software:



The program involves a loop that cycles through a certain set of tasks while providing the ability for the code to be interrupted by some input. Using interrupts with the buttons presses and the rotary encoder prevents situations where a signal is missed, misread, or debounced incorrectly. The display involves SPI communication with a display driver board that allows information to be presented on the TFT screen. The interface code refers to the communication with the ADC and DAC to read the current and voltage, and set the current and voltage. Other I/O functions deal with the tap selector and sense selector relay boards, the temperature sensor, and the fan controller.

Results

General Results:

Overall, the power supply worked very well and was able to hit all of its amended design requirements. There were no glitches that could be easily noticed when operating the system and the user interface made it rather convenient to use. In general, the supply was much easier to use than the HP units in the Texas Instruments design lab, and the noise was much less in amount.

Qualitative Analysis:

From a user perspective, the device was easy to operate and encountered no catastrophic failures. Such a concern was only logical in the initial tests because the control circuitry was not known to be either reliable or unreliable at that point. Luckily, relay switching for the taps occurred correctly and did not cause any shorts to occur between the secondary taps. Additionally, no gate over drive ever occurred during short circuit tests. This error would causes the pass transistors to reach near zero resistance and theoretically blow apart the current shunt's trimmed conductor.

Quantitative Analysis:

A large amount of measurements were made to test the performance characteristics of the power supply. A 6.5 digit NIST traced multimeter was used to make measurements of the calibration of the instrument in constant current and constant voltage modes. The voltage accuracy was around .01% while the current accuracy was .05%. Such an extreme level of accuracy can be attributed to the high quality op amps, the trimmed current shunt amp, the precision temperature compensated voltage reference, and the 32-bit DAC and ADC.

The noise performance and reactance was also quite superb. The RMS noise was measured at < 5mV, but this appeared to also be at the noise floor of the instrument in the environment. This test should be repeated in an RF-proof anechoic chamber. The supply was able to change from a higher to much lower current within 1ms for a high resistance load. Such a characteristic shows the fast ability of the supply to change the current output as a result of the small output capacitor. Additionally, the voltage showed no measureable deviations when connected to a rapidly changing load. Usually only able to be done with PID control, the extremely high bandwidth of the control circuitry allowed it to respond nearly instantly to any changes in output requirements.

Future Work

Next Steps:

The next steps for this supply are not necessarily improvements, but different methods of achieving the same result. While linear regulation is a low noise and simple idea to use, it is extremely inefficient and causes concerns for excess heat. The next steps for this system could include a move to switch mode voltage generation. Such a change would allow for much higher efficiency and a more compact and quieter system. Although switch mode power supplies are much noisier, the improvement in efficiency are tempting.

Conclusion

Operational Features:

The things that worked in this system are the TFT screen user interface, the keypad input, the rotary encoder input, constant voltage mode, constant current more, constant power mode, high speed load response, excellent noise filtering, ability to output at the original specifications, digital control, ability to output 0.0001 V, automatic fan response, emergency thermal shutdown, transistor load balancing, and very high accuracy. These features exceed what I expected to achieve in the time I had available.

Problems:

Some features that did not work were network interfacing over an Ethernet connection and the original gate driver. The microcontroller has native support built in for this sort of communication, but I did not have the time to program this feature in. The first gate driver I attempted to use had a very large gain and would put out 0 or 15 volts with no in between. As a result, the output capacitor would charge instantly and need to discharge. This occurred as a high speed and created a high amplitude saw tooth waveform to be created. Using an optoisolator allowed me to create the analog gate voltage I wanted.

Knowledge Gained:

An immense amount can be learned by attempting to create a high-power, precision, digitally controlled power supply from scratch. Since all of the circuits inside the system where constructed by me, I had to learn more learn about boost converters, 40-pin LCD operation, and SPI tri-state buffering. In addition, the actual process of creating the voltage regulator was complex and required tens of hours of testing and experimenting with different passives and different semiconductor components to improve performance. In the end, I can definitely say I have learned a lot more about power systems, thermal design, analog circuits, and digital communication.