

POWER CONTROL: DIGITAL FLEXIBILITY AT ANALOG PRICES

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ABSTRACT

Control circuitry for switching power supplies and motor drives typically come in one of two varieties: application specific analog components for minimum cost, or expensive digital systems for maximum flexibility and ease of use. Methodologies are presented that enable the best of both worlds to be achieved, resulting in digital flexibility at analog prices. These methodologies include: volume production through versatile design and standardization, realistic specification and designing to cost, assembling homogeneous design teams and performing wise trades. A design example with test data is provided to validate proposed methodologies. Future trends are then considered.

CHALLENGE

There is a substantial gap in the power electronics world that needs to be filled. Switching power supplies and motor drives with analog control circuitry can be purchased for hundreds of dollars, while the same power converters with full-featured digital controllers cost thousands of dollars.

The flexibility and ease of use that digital controllers provide is very attractive, but the cost is prohibitive for many applications. There is a strong need to develop digital power control technology at analog prices. To achieve this goal, proper design methodologies must be employed.

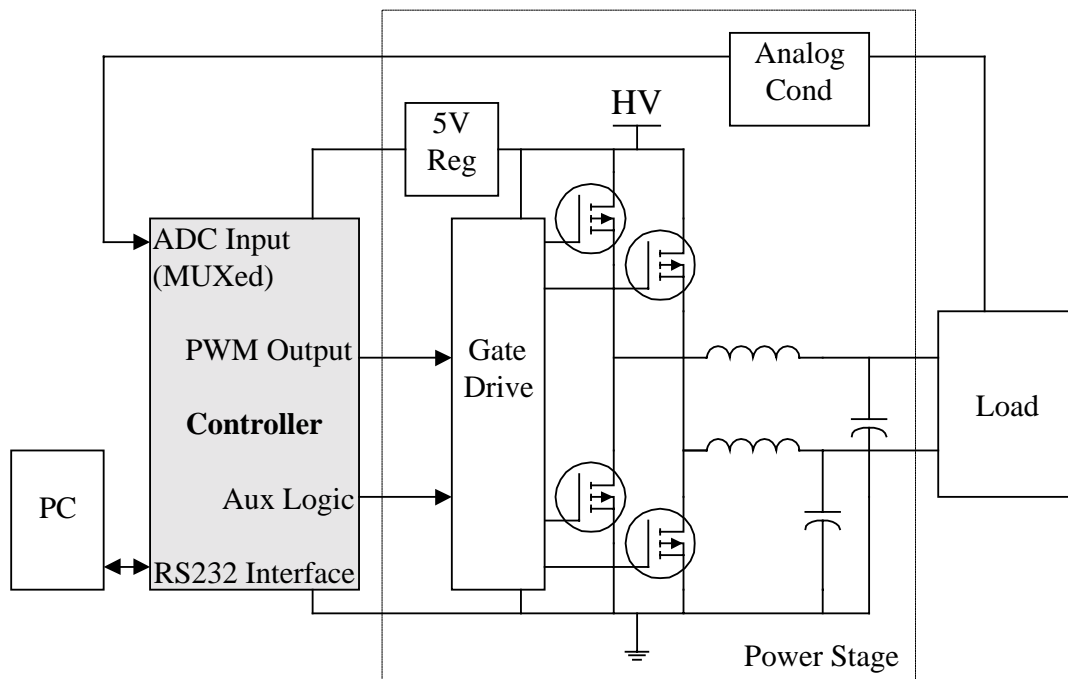


Figure 1. Simplified Schematic of Digitally Controlled Four-Quadrant Power Converter

METHODOLOGIES

Proper design methodologies are especially critical in digital power system development because teams are usually comprised of specialists working across disciplines: power electronics, magnetics, EMC, analog conditioning, digital hardware, processor firmware and PC software, control algorithms, test and manufacturing, as well as management.

Too often in this situation team members fight to stake out their territory rather than leverage each other's capabilities. A chief engineer with a working knowledge of these disciplines and interpersonal skills is essential in bridging this gap. This type of qualified individual is becoming increasingly scarce, but by generating designs that are truly versatile, a single design team may satisfy more product needs overall.

Examples of trades across disciplines to optimize performance and minimize cost of a digital power controller include:

- Adapting control algorithm implementation to complement microcontroller instruction set
- Offloading microcontroller firmware tasks to PC software for user interactive efforts
- Imprecise analog conditioning with calibration factors stored in nonvolatile memory at production
- Analog circuitry and discrete logic to aid microcontroller performance
- Firmware routines to facilitate test

To ultimately achieve powerful performance at a low price, some paradigm shifts are required. Reasonable specifications must be made with consideration to design-to-cost methodologies.

Overly conservative specification is easy, therefore common. It is much easier to find a solution that works, than to find the simplest solution that works. It is a terrible waste to discard an acceptable solution because it does not satisfy a specification that may be nonessential. Appropriate specification may be more time consuming, but development time must be weighed against production costs and redevelopment time.

Design-to-cost philosophies must be adopted from the start of the program. Goals and limitations must be clearly stated and followed throughout development. As projects rarely come in ahead of schedule and under budget, it is almost certain that a team will use all of the resources available to them.

For example, Phase A of a project calls for a functional prototype, while Phase B allows for cost and size reduction. If at the end of the first phase the team has built a rack of off-the-shelf equipment costing \$30,000, little has been done to satisfy the second phase goal of a \$1,000 product the size of a shoebox. If the same team starts with integrated power modules driven by an appropriate microcontroller, the second phase is a refinement effort rather than a redesign effort.

VERSATILITY

It is no secret that prices drop dramatically when the volume of production is increased. High volume in the power industry is often not accomplished because of the broad spectrum of requirements, which usually results in countless unique designs being developed. The key to generating a high volume design is to break out the subsystem that is most common and costly, then make it versatile enough to be applied to a wide variety of applications.

In the case of power converters, the control circuit remains virtually unchanged regardless of power or voltage level, making it a good candidate for standardization. The controller in Figure 1 accepts user commands and feedback, then outputs the appropriate state to the power switches, typically Pulse-Width-Modulated (PWM). Compensation is included to tailor the transient response of the controller for the specific application.

A microcontroller that contains the appropriate peripherals, such as Analog-to-Digital Converters (ADC), PWMs, timers, and serial ports can serve as a low cost power controller if properly implemented. The firmware contains the algorithms to be executed with key parameters set by the user for each specific application.

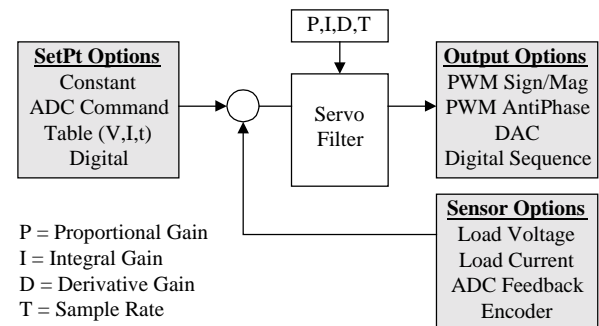


Figure 2. Versatile PID Control Loop with Selectable Parameters

Figure 2 illustrates this type of versatile control scheme. Selection of the feedback parameter allows the power converter can be configured as a voltage or current source, temperature or pressure regulator, or as a motion controller. The PID parameters are then adjusted to achieve the desired control bandwidth and stability margin.

Additional flexibility is accomplished by allowing the set point of the control loop to be varied by external signal, lookup table, or host processor. Selectable output switching sequences allow a variety of power stages to be driven:

- Anti-phase H-bridge
- Phase-modulated H-bridge
- Sign/magnitude H-bridge
- Push-pull
- Single ended

The operational parameters are selectable without additional programming and are stored in nonvolatile memory. A Personal Computer (PC) facilitates initial parameter selection, but the controller is capable of stand-alone operation after being configured.

Driving a four-quadrant power stage (capable of positive or negative voltages and currents), such as that in Figure 1, the following devices can be configured with the point and click of a computer mouse for stand-alone operation:

- Power Supply
- Motor Drive
- Electronic Load
- Power Amplifier
- Waveform Generator

Coupled with the power of a PC (without additional cards), critical laboratory equipment could be developed with a high-level computer program:

- Isolated Data Acquisition
- Automatic Test Equipment
- Servo Development Station

FEATURES

A digital controller was developed using a microcontroller chip containing multiple ADC, PWM, and serial ports. To support this chip, an oscillator, nonvolatile memory, and serial interface was added. The gate drive, 5V regulator, and analog conditioning circuitry of Figure 1 are considered to be part of the power stage since those components are more likely to be application specific. The total cost for the controller parts is under \$10.

Employing the outlined design methodologies, some innovative techniques were developed to satisfy performance and cost objectives. Program memory was traded for firmware execution speed. Enhanced ADC resolution was achieved with low cost external circuitry. Electrically isolated communication between the PC and controller was accomplished with opto-couplers biased off data lines. These techniques have been tested and proven.

In summary, key controller features include:

- Configurable and adjustable control loop
- Selectable switching schemes and frequency
- Parameter limits for protection
- Timed execution and measurement
- PID 80uS update rate
- PID gain range 0 to 50,000
- Condition dependent control gains
- 12bit effective control resolution
- Isolated addressable RS232 interface
- Parameter / table command uploads
- Operational parameter downloads
- Multiple DAC control

Primary benefits of these features include:

- Reduced Design Time
- Reconfiguration without PCB rework
- Overall system parts reduction
- Fully optimized transient response
- Nonlinear device simulation
- Sequenced start-up and shutdown
- Data acquisition capability

Figure 3 is sample screen from the PC parameter selection program. The end result is a device that can be configured to satisfy a wide variety of power applications quickly and easily at minimal cost.

Compare configuration of the control loop through the PC program to conventional processes. Switches and pots are set (or the board is reworked) then signal injection and transient capture equipment is synchronized. Not only is this process time consuming, but also sensitive circuitry is exposed to ground loops and antennas created by test equipment connections in a noise ridden environment.

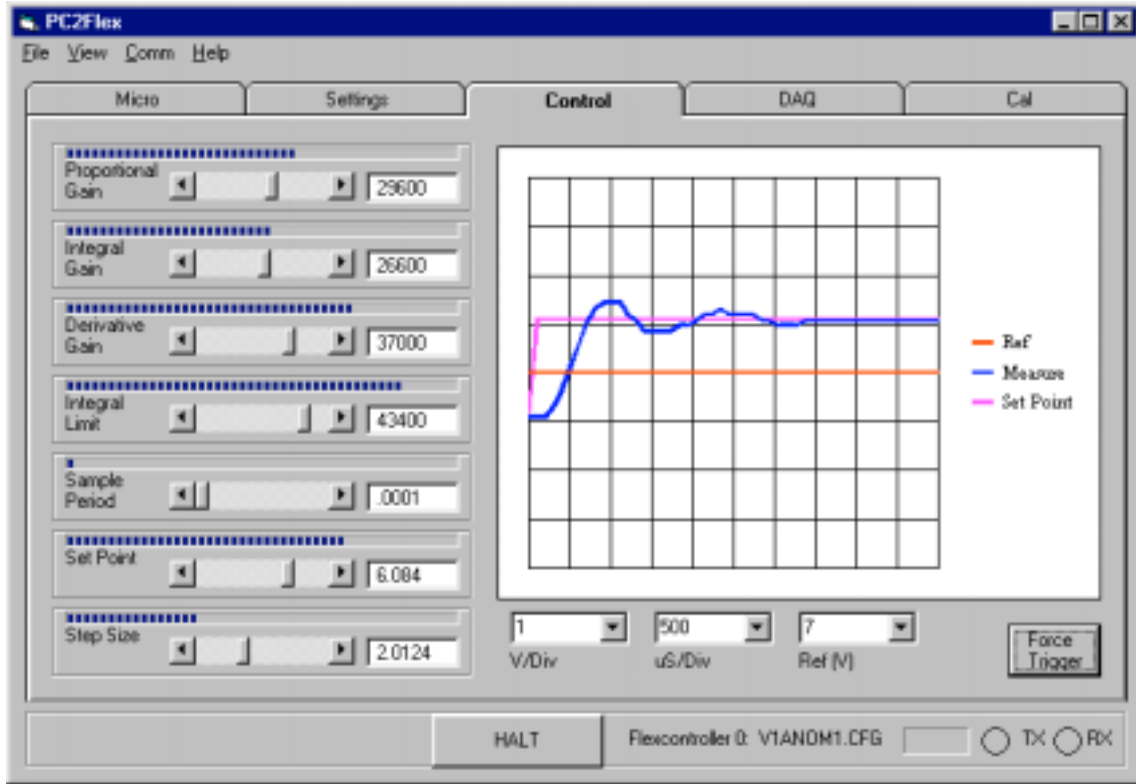


Figure 3. Sample Screen from PC Parameter Selection Program (Control Loop Configuration)

APPLICATIONS

The proposed design methodologies are validated through performance data. The three examples shown are a programmable power supply, solar array simulator, and motor controller, although countless others are possible. All were configured from the same hardware through the PC parameter selection program.

An H-bridge power stage, similar to that shown in Figure 1, was built with 24V input and 0.75A output. This small power stage was chosen for convenience, but the concepts are valid at any power level.

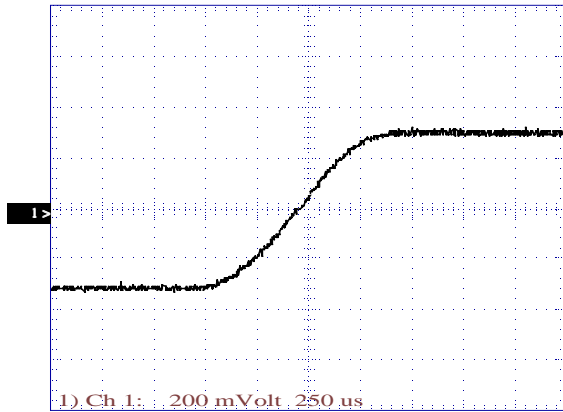


Figure 4. DC/DC Converter Step Response (200mV/div, 250uS/div)

Figure 4 is the step response of a programmable power supply where the set point was changed from 5.0V to 5.6V in enhanced resolution mode (12bit effective). The output voltage can be set via PC to any voltage from +17V to -17V in 10mV increments ($34V/10mV=3,400$ or $\sim 2^{12}$). The high PID update rate and wide gain range allow a fast stable response rivaling analog power supplies.

An H-Bridge converter is used in this example, but virtually any power topology is possible, including:

- Flyback
- Buck
- Forward
- Boost
- Half-Bridge
- Synchronous Rectifier
- Power Factor Correction

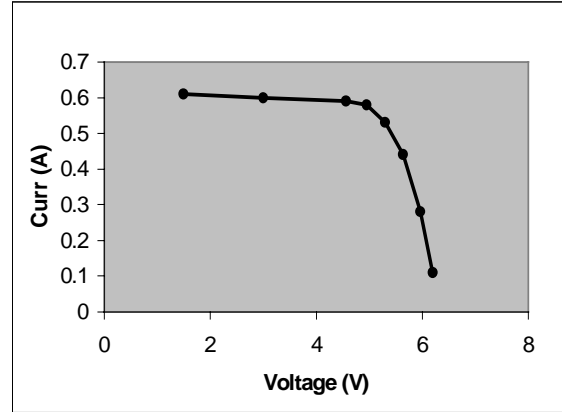


Figure 5. Solar Array Simulator Test Data (Voltage controlled current source lookup table)

Figure 5 is the Current vs. Voltage profile for a solar array simulator. The controller was configured as a voltage controlled current source. A lookup table based on test data was downloaded through the PC program to define the I-V relationship. Nonlinear applications such as this are far easier, and more adjustable, through digital means.

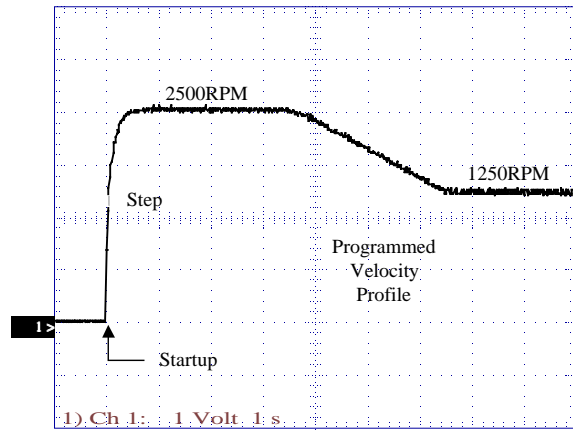


Figure 6. DC Motor Tachometer Response (Processed encoder output)

Figure 6 is the tachometer response of a DC motor. The controller calculated velocity based on the period of encoder pulses then output the information through a DAC to aid data acquisition. The motor was stepped to final velocity to demonstrate control, then followed a programmed velocity profile, which can be any desired waveform.

The adjustable update rate of the PID loop allows slower processes such as motion and temperature control to be accommodated. It is also possible for the controller to incorporate functions normally provided by a programmable logic device, minimizing the overall system component requirements.

VISION

The future can often be predicted by looking at the relevant past. Decades ago designers painstakingly developed op-amps and linear regulators from discrete transistors, but today it would be considered foolish not to use drop-in integrated circuits for most applications.

The power designer still painstakingly develops his products with dozens of discrete devices and conventional tools, much as he would have decades ago. Considering the declining supply of craftsman skilled in this art form and the increasing demand for power products, a better way is needed.

Digital designers, for example, have progressed to the point that they can complete a design at their PC in a single sitting. CAD programs convert boolean expressions to logic gate configurations, then allow simulation and verification before downloading complete designs to a single chip.

The trend toward automating the power design process is underway. Prefabricated magnetics and integrated power modules (multiple transistors and diodes in a compact package) are becoming more popular. Smart power modules are available that contain gate drive, current limit, and thermal shutdown circuitry. These modules ease design efforts but are not yet smart enough.

Power designers deserve the same conveniences given digital designers. As a computer simulation is completed, so should the design effort, complete with a parts list of *available* components. SPICE provides the user with devices like voltage controlled current sources based on lookup tables, but most electronic distributors don't carry these devices. However, they could tomorrow if we take the appropriate steps today. Low cost is essential in enabling the volume production needed to turn this vision into reality.

CONCLUSION

Design methodologies have been presented to assist in the development of versatile and inexpensive digital power controllers. This effort is intended to benefit the power industry by easing future design efforts and ultimately decreasing production costs.

These methodologies were validated through the design and test of a full-featured digital controller. This device, for which patent protection is being sought, can be fabricated with less than \$10 in components.

REFERENCE

[1] R.R. Boudreax, R.M. Nelms, John Y. Hung, "Microcontroller Implementation Dictates Ultimate Performance of Digitally Controlled DC-DC Converters," PCIM Magazine, December 1996.