TRENDS IN THE USE OF DIGITAL TECHNOLOGY FOR CONTROL AND REGULATION OF POWER SUPPLIES*

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Abstract

Since the availability of computers, accelerator power supplies have relied on digital technology in some way, from such simple tasks as turning the supplies on and off to the supplying of computer-controlled references. However, advances in digital technology, both in performance and cost, allow considerably more than simple control and monitoring. This, coupled with increasing demand for higher performance and monitoring capabilities, has made it appealing to integrate such technology into power supply designs. This paper will review current trends in the use of such advanced technology as embedded DSP controllers, and the application of real-time algorithms to the regulation and control of power supplies for accelerators and other large-scale physics applications.

1 INTRODUCTION

Technological advances in digital signal processors (DSPs), networking, microprocessors, and programmable logic devices (PLDs) have empowered designers with entirely new techniques and methodologies that were economically unthinkable two decades ago. These advances, along with increased performance demands, have fueled the push of digital technology deeper into the controlled devices. The justifications often quoted for this push to digital include reproducibility, increased stability, increased resolution, and decreased infrastructure costs (networks replace control wiring).

This paper attempts to survey the extent to which digital technology has been applied to the control and regulation of power supplies used in accelerators. The information presented was obtained through personal contact and a literature search. The examples cited are intended to be representative of digital applications to accelerator power supplies, and are by no means an extensive survey of all efforts.

2 A GENERIC MAGNET POWER SUPPLY

Figure 1 shows a typical power supply block diagram. The power circuit converts incoming AC power to the form required for the magnet load (usually DC). Power

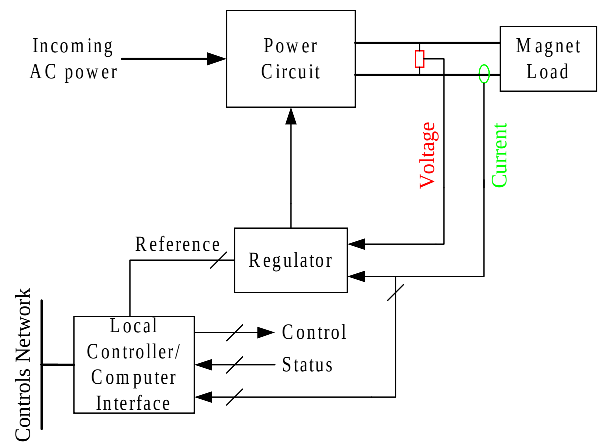

Figure 1: Generic Accelerator Magnet Power Supply

control is generally achieved using silicon-controlled rectifiers (SCRs) or switched-mode DC choppers [1]. Although these types of power circuits are inherently analog, they can be viewed as a sampled-data system, since the output power can only be changed at discrete intervals in time.

Historically, power converters used phase-controlled rectifiers operating at AC line frequencies, but these are inefficient at low voltages and have poor regulation bandwidth. Switched-mode power converters have wider bandwidth, but also generate higher electrical noise levels, and applications are limited by the availability of fast high-power switching devices. Over the past two decades, however, the availability of fast high-power switching devices has increased dramatically, making it possible to consider switched-mode topologies for all but the highest power applications.

The regulator, which may be analog or digital, controls the power circuit, ensuring that the magnet output current matches the reference signal from the accelerator control system in the presence of AC line fluctuations and environmental changes. The regulator may use both voltage and current signals in the feedback loops.

The local controller, which may be an embedded processor or a simple computer interface, provides the means to remotely control and monitor the power supply from the control system. Note that Figure 1 does not show any A/D or D/A converters. Their placement depends on the implementation of the power supply regulator, i.e., analog or digital.

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3 ANALOG VS DIGITAL REGULATORS

While frequency-domain analog regulator schemes have predominated in the industry, digital regulators offer several advantages that make them attractive, such as the possibility of more advanced and functional control methods, less susceptibility to parameter variations from thermal effects and aging, and less sensitivity to noise. A major advantage of the digital regulator is the possibility of changing regulator dynamic behavior through software changes. However, while component costs are dropping considerably, there is little doubt that digital regulators are more expensive and complex to develop than their analog counterparts.

Digital regulators are particularly well suited to more complex control applications, since they facilitate the use of more modern 'optimal' control methods (state-space, robust, fuzzy). For example, the Large Hadron Collider (LHC) has prototyped an 'RST' controller that allows a desired tracking behavior (following a reference) to be obtained independently of desired regulator performance (disturbance rejection) [2]. Systematic effects, dead-bands, and other nonlinear effects are also easily incorporated.

Digital systems can also offer advantages where very high precision is required or where long time constants are involved. For these reasons, LHC chose digital regulation to meet their 1-ppm power supply stability and tracking requirements [3].

4 POWER SUPPLY CLASSIFICATIONS

We have attempted to classify accelerator power supply controllers based on the location of the local controller and implementation of the power supply regulator.

4.1 All Analog – Local DAC/ADC

Perhaps the most common configuration has a digital-to-analog converter (DAC) to generate an analog reference and an analog-to-digital converter (ADC) to monitor output, both local to the power supply with an external local controller [4]. The power supply frequently is of commercial origin. The local controller delivers an analog reference to the power supply, monitors analog readbacks, provides digital I/O lines for control and status, and communicates with the control system via a network. The ADCs and DACs are typically 12- to 16-bit devices although there is a push to higher resolution. The authors have been informed of a design in routine use at SLAC that offers 21 bits of effective resolution. This scheme uses a 16-bit main DAC with an 8-bit DAC to extend the resolution to 21 bits. A microprocessor is used to continuously calibrate the DAC against a stable reference [5].

Very often the local controller can be located in a single chassis, such as VME, a short distance from the power supply. In many cases, however, the need for high precision analog setpoints and readbacks requires that the ADC and DAC be located as close as possible to the power supply so as to minimize noise pickup. One method of achieving this is to embed the ADC and DAC inside the power supply chassis and have a purely digital interface going to a local controller CPU [6].

4.2 Embedded Processor – All Analog

The next level of digital integration embeds the local controller CPU within the power supply [7-10]. This has become increasingly practical with the availability of inexpensive microcontrollers and large-scale integrated circuits. This approach has the benefit of simplicity, uniformity of interface, and reduced infrastructure costs through the replacement of control wiring with a network connection. The extra computing power can allow advanced functions to be incorporated, such as feedforward orbit correction based on insertion-device gap settings [11].

4.3 Embedded Processor – Digital Current Regulator - Analog Voltage Regulator

In systems that require high performance, it is common to use an external current regulator that controls a conventional power supply operating as a voltage source. While the external regulator is frequently analog, these situations are ideally suited to a hybrid regulator approach, where a digital processor implements the current regulator and feeds analog voltage demands to the power supply via a DAC.

In this type of system a digital processor reads the digitized current from an ADC (often connected to a DCCT), passes the value through a digital regulator, and sends the result to a DAC to generate an analog signal for the power converter voltage loop. Such a system was implemented at KEK in the late 1980s [8].

This type of system is planned for the LHC project at CERN where groundbreaking work has been done in high precision control of very high current power supplies [12]. In this application, the current flowing through superconducting magnets will be ramped to 11 kA over a period of 30 minutes, with a required precision and stability of around 1 ppm. Implementing such a system, especially with the very long time constants, is exceptionally challenging and would be all but impossible with analog circuitry. The feasibility of such a system has been demonstrated at the 1-ppm level [3].

4.4 Embedded Processor – All Digital Regulator

Our final classification is the "all digital regulator." What distinguishes this type of power supply from that discussed in the previous section is the direct digital control of the power circuit, eliminating the need for a DAC at the output of the regulator. Examples using a digital pulse width modulator (PWM) to directly control the power devices in a switched-mode power converter are described in references [13] and [14].

There are several examples of such systems in various stages of development. The Swiss Light Source will use all-digital systems for its magnet power supplies. Pre-production units are under test and orders for 575 production units are in process [15]. Development is underway at various other labs, including Daresbury [12] and the Advanced Photon Source (APS). The APS is developing an all-digital regulator as a possible performance upgrade to its power converters.

5 DIGITAL POWER CONTROL

5.1 Digital Phase Control

Many high power supplies use phase-controlled rectifier circuits, frequently silicon controlled rectifier (SCR) based, as the power control elements. The output voltage can be reduced from the maximum value by delaying the triggering of the SCR devices relative to the zero crossing of the incoming AC line voltages. Digital phase control of SCRs has been used in accelerator power supply applications since 1983 [16], and a patent has been issued [17].

To achieve precise control, the triggering circuits require an accurate indication of the actual zero-crossing times of the incoming AC line. Since the incoming AC lines are generally not clean enough to do this directly, a conditioned line reference signal must be generated.

A typical system uses a conditioned power line reference as an input to a phase-locked loop (PLL). The phase-locked loop multiplies the line frequency to a much higher frequency that is then used as a clock for digital SCR trigger timing circuits. For example, the SCR firing circuits for the APS booster synchrotron ramped magnet power supplies contain a conventional phase loop (using an analog loop filter) that multiplies the line frequency (60 Hz) by 5000. The National Synchrotron Light Source (NSLS) booster power supplies use an all-digital phase-locked loop that multiplies the line frequency by 98,304 [18].

A PLL output is used to generate a multiphase clock, which is the time reference for each of the SCR trigger circuits. The multiphase clock defines "0" degrees for each of the power source phases. SCR trigger pulses are generated by counters clocked by the PLL high frequency clock output. The relationship between SCR firing angle and power circuit output is a nonlinear arc-cosine function. This function may be linearized via a lookup table or DSP algorithm. If the demand signal is analog, an ADC is required.

A potential problem with phase-controlled power supplies is subharmonics caused by an imbalance in the source line phases and transformers and differences in the SCRs. Subharmonics are difficult to filter, and if they are filtered, the dynamic response of the power supply is adversely affected. Phase-to-phase errors can be compensated for by using measurements of each phase's voltage and zero crossing time and adjusting the trigger time of each phase to compensate for differences. Such a correction is described in reference [19].

5.2 Digital PWM Generators

The output of a switched-mode DC-DC chopper is a function of the percentage on time of the power switch, which is in turn controlled by the regulator.

An analog pulse-width modulator usually consists of a resettable ramp generator running at the switching frequency (say 20 kHz) and a comparator. The digital equivalent is typically implemented in a programmable logic device (PLD) as presettable counters. While the resolution of an analog PWM is theoretically infinite (ignoring noise effects), the resolution of the digital PWM is determined by the counter clock period and the repeat rate of the PWM output, and may be expressed as *Tc/Trep*, where *Tc* is the counter clock period and *Trep* is the time between PWM outputs. As an example: for a counter clock of 100 MHz and a PWM output rate of 20 kHz, the PWM resolution is 200 ppm, which is equivalent to between 12 and 13 bits. Faster PLDs with clock multiplication could permit counter clock rates in the few 100 MHz range. An example of a PLD-based digital PWM controller is given in reference [14].

Achieving PWMs with resolution equivalent to 18 bits or greater with a pure PLD counter solution is at best difficult with presently available components. For a 20-kHz PWM output rate, the counter would have to operate at better than 5 GHz, well beyond the capabilities of present day PLDs.

One can achieve and in fact exceed 18-bit resolution by interpolating between counter clock ticks. Such a PWM circuit is described in reference [20]. The interpolator can be any digitally controlled delay circuit that can deliver the requisite resolution. The complication added through the use of an interpolator is the need to mesh the interpolator operation with the PLD counter to produce a monotonic output. This monotonic meshing requires the services of a processor to allocate demand values between the counter and the interpolator.

6 SPECIAL TOPICS

6.1 Ramping Power Supplies

An early application of microprocessor technology to accelerators has been the control of power supplies used in machines with fast energy ramps.

All accelerators require excellent matching between currents in the main dipole bus and the corresponding quadrupole magnets. This can be particularly challenging in accelerators where the particle energy must be ramped. One approach has been to use a resonant power circuit and sinusoidal acceleration cycle, but this usually requires a large capacitor bank and fast cycle rates [21].

Meeting the tracking and stability requirements can be exceptionally challenging when using a nonresonant power circuit, such as a phase-controlled power supply, because of power supply transients and low regulator bandwidth. The solution is to provide a feedforward voltage waveform to the power supply that corresponds to the voltage needed to drive the desired current waveform through the magnet load. By taking advantage of the cycle-to-cycle repeatability of the system, it is possible to successively modify the feedforward waveform based on the measured current ramp from previous cycles to reduce systematic errors in output current.

The first application of digital control to this problem that is known to the authors was done at NSLS in the early 1980s [19]. More recent examples include KEK's main ring power supplies [22], and Fermilab's 'MICAR' system [23]. The general approach is shown in Figure 2.

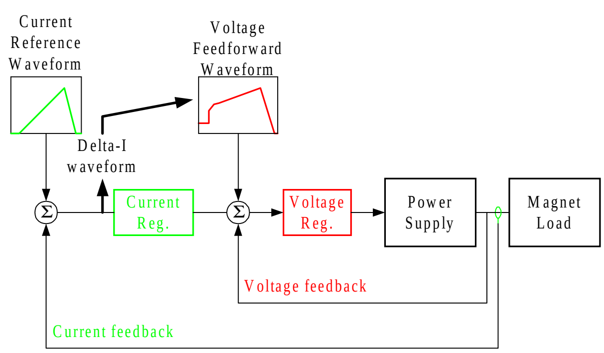

Figure 2: Ramping Power Supply Block Diagram

Initially a voltage feedforward waveform is computed from the desired current output waveform and the known load characteristics. The resulting output current waveform is compared with the desired output and the residual error is used to modify the feedforward waveform. The optimal feedforward waveform is therefore "learned" over many ramp cycles. More recent systems integrate the feedforward and current feedback in a single digital system [24].

6.2 Power Supplies and Accelerator Feedback

As accelerator performance requirements increase and accelerator control systems become more capable, power supplies are becoming a more integral part of accelerator feedback systems. Applications may be implemented on a workstation, in local controllers, or in dedicated real-time hardware. Examples include injection trajectory control, orbit control, and rf cavity control.

It is sometimes necessary to control the trajectory of extracted beam from circular accelerators. This can be accomplished by controlling extraction pulsed magnet strengths based on transfer line beam position monitor readings. Such a system is in use at the APS for injection into the storage ring from the booster synchrotron [25].

Feedback systems for orbit control integrate corrector magnet power supplies within a feedback loop that controls the particle orbit in the accelerator based on beam position monitor readings. While the power supplies themselves are not necessarily digitally controlled, it is virtually a requirement that the orbit control system be implemented digitally. Typical applications use many beam position monitors and make changes to many correctors at rates of 1-4 kHz. One of the more recent examples is described in reference [26].

There is much activity in the area of digital control of rf cavity field amplitude and phase [27-28]. Digital feedback is being used to provide compensation for systematic error sources such as Lorentz forces [27], to correct the cavity tuning control loop [28], and to reduce higher frequency modes to improve beam stability [29].

Los Alamos National Laboratory is planning to use DSPs with adaptive feedforward and feedback to provided klystron cathode voltage pulses with about 0.5% fidelity [30]. The DSP will provide closed-loop regulation of the cathode voltage along with a prediction algorithm for capacitor bank droop.

7 OTHER POWER TECHNOLOGY APPLICATIONS

Digital control of power converters has been an active area of research since the advent of microprocessors in the 1970's [31-33]. While work outside the accelerator community has been focused on DC-AC inverters primarily for motor control (due to associated nonlinear control problems), there has nevertheless been active interest in pursuing microprocessor-controlled DC-DC converters and phase-controlled power supplies [34-36].

8 CONCLUSION

We have attempted to survey the application of digital technology to accelerator power supplies. We anticipate that the infiltration of digital techniques into power supply design will accelerate as performance demands increase and knowledge of the techniques is disseminated to the accelerator power supply community.

9 ACKNOWLEDGEMENTS

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