Five years of operational experience with digitally controlled Power Supplies for beam control at the Paul Scherrer Institut (PSI)

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Abstract

Precise beam control is a crucial requirement for the operation of particle accelerators. High-precision power supplies for beam guiding are essential. For the Swiss Light Source a new digital power supply control technology was developed and implemented. A large number of power supplies are equipped with this compact and flexible control system at PSI. Practical experiences of five years of operation are presented.

Introduction

The Swiss Light Source (SLS) is a third generation synchrotron radiation source, which is designed to deliver high brightness photon beams to various experimental stations at the same time. The stability and the reproducibility of the electron beam (electron orbit) is one of the most important properties of the particle accelerator. Therefore about 580 high-precision magnet Power Supply (PS) units for beam control – ranging from +/-7A, +/-20V up to 950A, +/-1000V – were installed in the SLS (table I).

A new digital control technology was developed and implemented in these precise magnet PS units in close cooperation with two companies [1], [2]. This 'Digital Power Supply Control System' (DPSCS) provides a number of advantages in comparison with conventional analog PS control technology (see also figure 1):

- Identical control hardware for various PS types (modularity)
- Flexibility (e.g. adaptations to different power converters and magnet loads)
- Advanced monitoring and diagnostic functions
- Digital link to the accelerator control system
- Simple and rapid device commissioning
- New device functions, such as arbitrary waveform generation or data logging

Due to the positive experience at the SLS, the digital control technology has been transferred to other machines at PSI, as well as to other institutes.

[1] SLS controls group
[2] Power Electronics group

- 60MHz DSP/FPGA system with 32/40 Bit floating point ALU
- Additional 256kB SRAM and 1MB FLASH
- Hardware watchdog
- 5MBaud fibre-optic link; average latency time < 35 µs; 10’000 write cycles per second
- Local service interface (RS232, JTAG)
- External trigger interface
- Clock deviation < +/-2.5ppm (-30°C to 75°C)

- Digital Pulse Width Modulation with 16-Bit resolution (PWM)
- PWM control for two independent H-bridges (1Q, 2Q, 4Q systems)
- PWM frequencies (implemented): 7.14, 10, 12.5, 16.7, 20, 25, 33.3, 50 and 100 kHz
- PWM synchronization between several power supply systems

- Eight 16 bit AD converters (50ksps/channel), electrically isolated
- Temperature stabilized voltage reference source
- Two 14 bit DA converters (50ksps/channel), electrically isolated
- Latency between data acquisition and power semiconductor addressing < 35µs
- 12 isolated digital inputs and 8 isolated digital outputs

- Advanced monitoring and diagnostic functions
- Arbitrary waveform generator with 11 memory cells (up to 16’384 data points each)

- Supply voltage range: 18-36V (max. 20W)

Fig. 1: Summary of DPSCS (DSP/FPGA- and ADC/DAC card with backplane)

Table I: Installed power supplies in the Swiss Light Source

Number of devices	Current [A]	Voltage [V]	Power [kVA] ([kW])	Switching frequency [kHz]
1	950	+/-1000	1000 (174)	10 (x)
1	500	880	440 (430)	16.7 (xx)
6	120	75	9 (9)	100
2	140	+/-120	17 (4.05)	50
24	140	60	8.4 (4.9)	100
3	120	240	28.8 (28.8)	25
4	145	70	10.2 (10.2)	50
2	120	130	15.6 (15.6)	25
150	120	60	7.2 (3.6)	100
4	120	60	7.2 (7.2)	100
18	120	15	1.8 (1.8)	100
2	+/-40	+/-40	1.6 (1.6)	100
3	+/-6	+/-110	0.66 (0.66)	100
356	+/-7	+/-20	0.14 (0.14)	100

(x) : Multi stage unit, PWM frequency at load: 40kHz
(xx) : Multi stage unit, PWM frequency at load: 66.6kHz

Digital Power Supply Control System (DPSCS)

All the PS units in the SLS are equipped with identical control hardware. The principle of a digitally controlled PS is shown in Fig. 2:. The main components of a PS system are:

- Controller board based on DSP and FPGA[1]
- AD/DA-Data acquisition board
- Power converter(s)
- Current measurement system (DCCT[2])

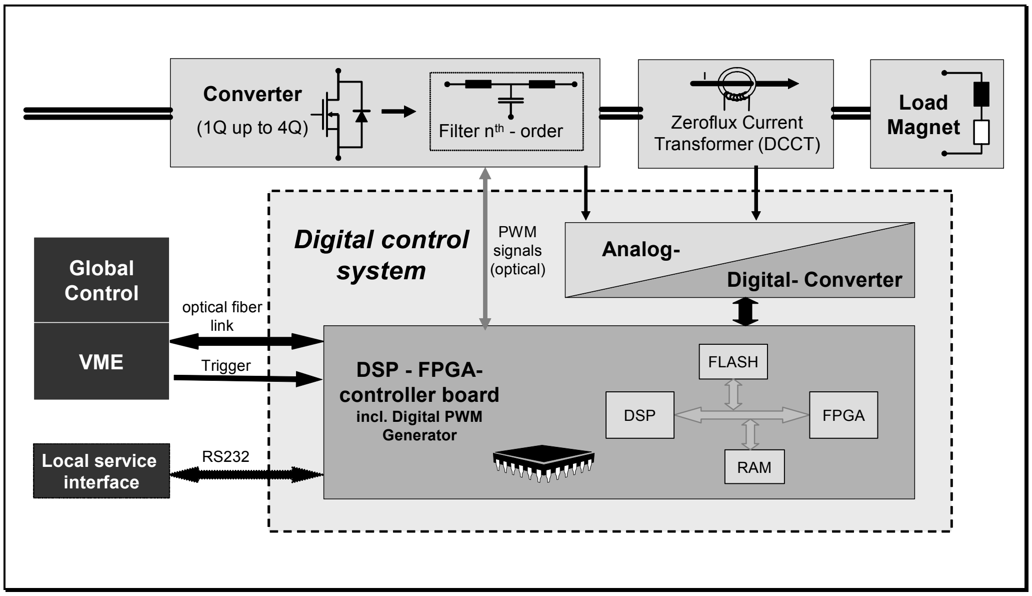

Fig. 2: Principle of a digitally controlled Power Supply

All device control functions such as control loops, monitoring functions or PWM[3] are implemented in software (C/C++) or in reprogrammable logic (VHDL).

For the data exchange (reference values, internal signals, configuration parameters, diagnostic information, etc.) each PS unit is connected via a 5Mbit optical fibre point-to-point link to the accelerator control system (VME[4]). To facilitate the connection to other systems, the link is optionally configurable as a RS232 compatible link. The data format for analog signals is based on the IEEE-754 32-bit floating-point format to avoid resolution and standardization problems. A write throughput rate of 10'000 data values per second is guaranteed, as well as an average latency time of 35 microseconds for setting new data values (e.g. reference values). A separate RS232 and a JTAG interface are available for maintenance purpose (local control).

Data acquisition board[5]

A high-precision analog to digital conversion is necessary for the measurement of the power converter output current. A resolution of better than 10 ppm (parts per million), corresponding to 18 digits, is required to fulfil the demanded PS specifications for the SLS. The current measurement is performed by

[1] Digital Signal Processor, Field Programmable Gate Array
[2] Direct Current Current Transformer
[3] Pulse Width Modulation
[4] Versa Modular European
[5] The used measurement principle is patented by PSI

16-bit SAR[1] analog to digital converters (ADC), together with a temperature stabilized voltage reference source. Over-sampling and filtering ensure the desired quality of the current measurement. The maximum sampling rate is 200k samples per second. Four more 16-bit ADC can be used for voltage measurements in the power converter(s).

Controller board

The core of the controller board consists of a digital signal processor (DSP) with floating-point capabilities and a field-programmable-gate-array (FPGA). The card is equipped with 12 isolated digital inputs and 8 isolated digital outputs. The switching signals for the power semiconductors (PWM signals), the external trigger signal and the interface to the control system are fed via fibre optic links. Several controller boards can be interconnected via a 20MBit link, in order to get a multiprocessor system.

The main functions of the FPGA are the digital Pulse Width Modulator (PWM) logic and the communication interface. The system is designed for the control of two independent H-bridges. To achieve a PWM resolution of 16Bit at all PWM frequencies, sophisticated methods were applied [3]. A Watchdog, I/O diagnostic functions and a high precision timer with a separate trigger input complement the functionality of the FPGA.

The DSP real-time software consists of multiple control loops (see example in figure 3), monitoring functions, diagnostic functions and other device functions. The hard- and software interface to the EPICS[2] based accelerator control system is identical for all power supplies and enables the data exchange of various device data. The DPSCS also provides remote maintenance capability.

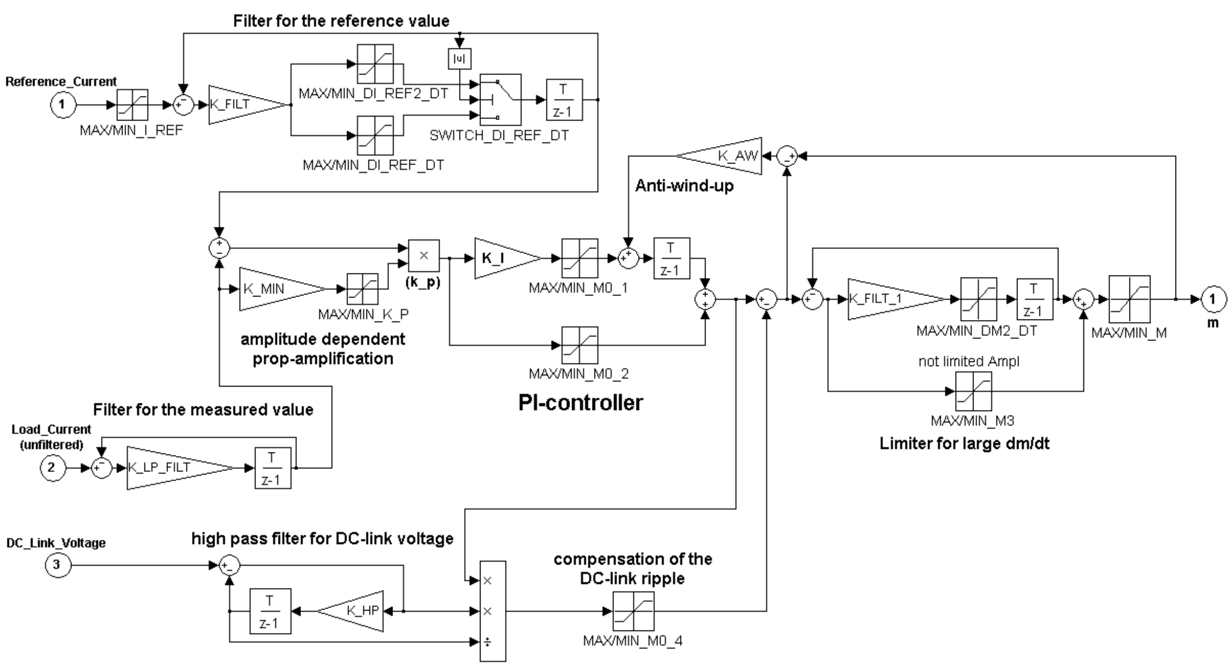

Fig. 3: Example of a control structure of a digitally controlled PS

Another important feature of the DPSCS is the possibility to run user-defined reference signal waveforms. With this function, a PS unit can be used as an arbitrary waveform generator (figure 4). An external trigger input and 11 waveform memory cells with a capacity of up to 16'384 data points each (32-Bit floating-point format) are available for this function.

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1 Successive Approximation Register

2 Experimental Physics and Industrial Control System

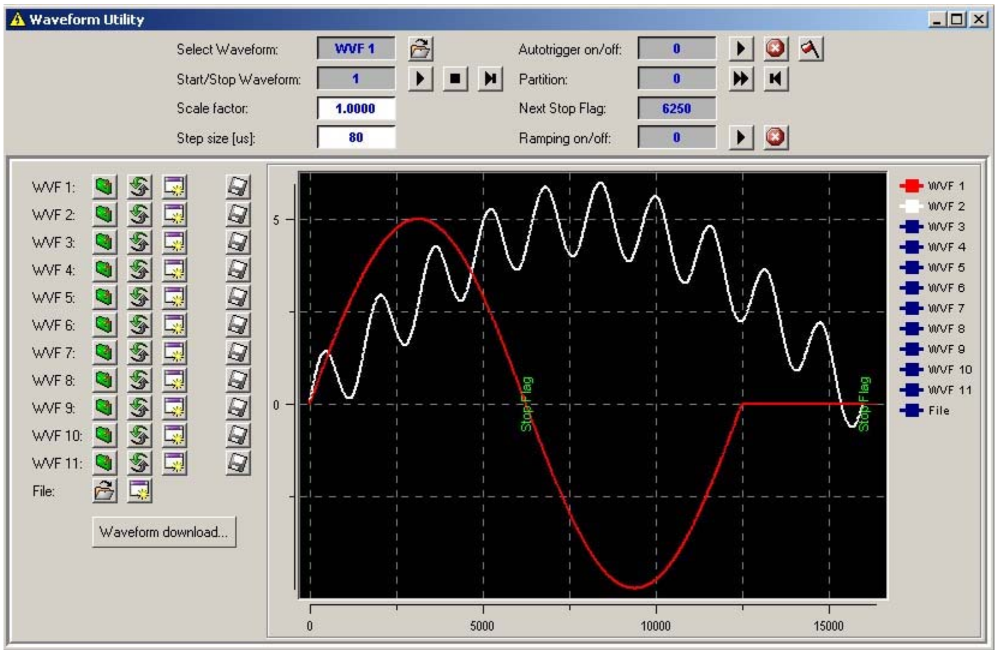

Fig. 4: Arbitrary waveform generator with two different waveforms shown

Experience and results

The operational experience with the DPSCS was very positive from the perspective of the developer as well as the user (see chapter “User progress report”).

The technical requirements of the power supplies at the SLS (precision, resolution, reproducibility, stability, etc.) were achieved at first go with the DPSCS. No out of range long-term drift or other stability problems were observed during the last four years of operation. The beam quality and the performance of the SLS, as well as the feedback of the various users, prove the chosen PS technology [5] [6] [7].

The features of DPSCS turned out to be very useful: With the digital communication link to the accelerator control system, no electromagnetic interferences occur in the reference value transmission. The chosen 32-Bit floating-point data format eliminates all data conversion problems between the control system and the power supplies. The advanced monitoring and diagnostic functions speed up the failure localization and minimize the repair time after a failure. Some features are essential parts of the accelerator control principle (e.g. the arbitrary waveform generation).

Commissioning and control system integration of a new PS can be done with a minimum of time. The Windows based service software with extensive graphical user interfaces facilitates the handling of the DPSCS for commissioning, maintenance and troubleshooting.

Availability and Reliability

During the first phase of the SLS commissioning – from 1999 to the middle of 2000 – about 130 PS units were required for the operation of the accelerator (commissioning of the linac- and booster- facility). By the end of 2000 this number increased to about 500. With the build up of the beamlines for the experimental stations the number of PS devices has reached 576 units now.

Since the beginning of 2001 all failures or troubling events, reported form the operators or from the maintenance staff, were logged. Figure 5 shows the reported PS failures during the last four years of operation. Fortunately, not all of them caused a beam loss of the accelerator. The graph can be subclassified into four groups of event types:

1. **Failures of subcomponent with production error:** A production error of a subcomponent – mounted on the DSP-FPGA controller board – effected that many DSP-FPGA controller cards had to be replaced during the first years of operation. The problem was fixed in the end of 2003 by replacing the component on all controller boards.
2. **Failures of the controller board (DSP-FPGA board)**
3. **Failures of data acquisition board:** E.g., a failure of an ADC on board.
4. **Other Power Supply failures:** Includes all failures of the PS units exclusive the failures of the DPSCS (group 1, 2 and 3). Fans and auxiliary power supply tend to be the problem!

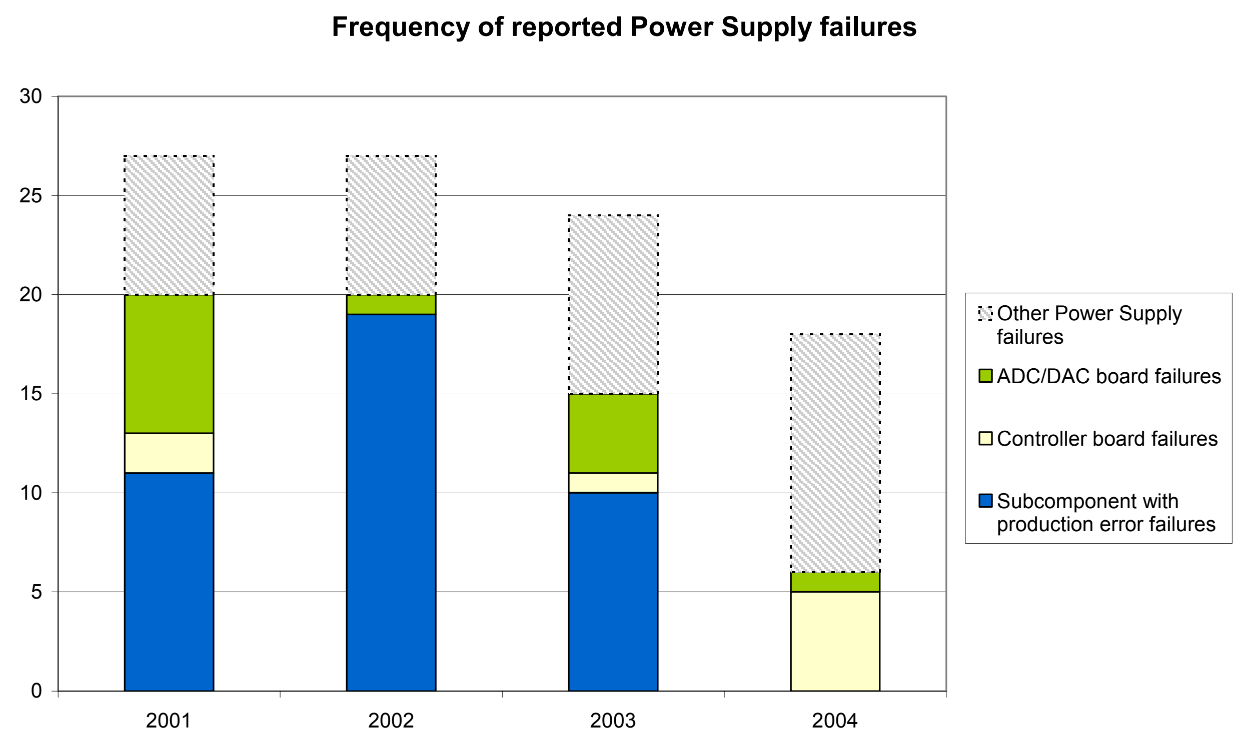

Fig. 5: Frequency of reported events from 2001 till 2004 (total of devices 2004: 576)

As it can be seen from the graph, the failure rate of the controller boards was reduced significantly since all components with production error were replaced.

Based on the logged failures rates the MTBF of the DPSCS is estimated in Table II:. The calculation was made with linear distribution of the failures versus time and with the following simplification:

$$MTBF = n * t / k$$

n: Number of devices
t: Test time
k: Number of failures

Table II: MTBF of the DPSCS

	31.12.2001	31.12.2002	31.12.2003	31.12.2004
Total Number of devices (mean value per year)	526	550	564	576
Total Number of DPSCS failures since 01.01.2001 (failures of subcomponent with production error are not included)	9	10	15	21
Test time (start: 01.01.2001) [hours]	8’760	17’520	26’280	35’040
MTBF of the DPSCS [hours]	511’973	963’600	988’128	961’097

Flexibility – new applications based on the DPSCS

In the meantime, all new PS developed at PSI are equipped with the DPSCS. This applies to the SLS, the proton accelerator, the neutron source as well as for other research facilities. Particularly for the proton accelerator – a facility that is up to 30 years old – several new PS applications were developed and realized with the DPSCS. At present, an innovative proton therapy facility is being built at PSI for the treatment of cancer.

The following enumeration contains some examples of power supplies using the DPSCS:

- Kicker converters for fast beam bending: These PS units toggle the output current between two values (triggered by an external source) [8]
- Twin Converter PS: A PS system with two power converters connected in parallel and a current balance controller (realized with one DPSCS unit).
- Tandem PS (see figure 6): Two serially connected power converter units consist of a buck converter and an H-bridge each. The system is realized with two controller units, which are linked by the internal data bus (master - slave system). A similar structure – consists of six power stages and four controller units – is used for the SLS booster bend PS [9].
- Various PS units with multiprocessor control systems: Systems equipped with up to four controller units for the control of several power converters.

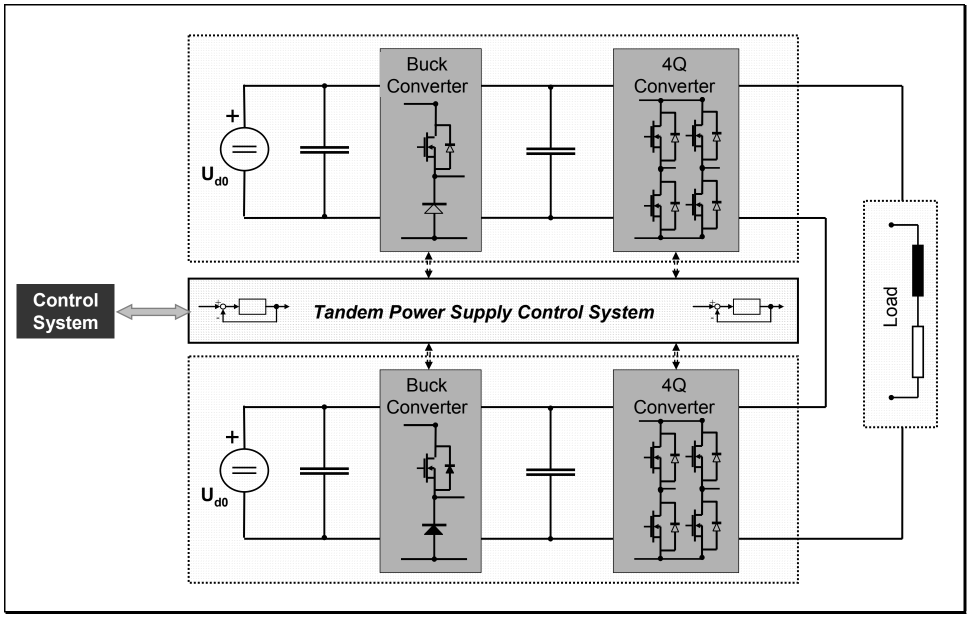

Fig. 6: Structure of the Tandem Converter Power Supply

User progress report

«The excellent stability of the digitally controlled power supplies was one of the key ingredients for the success of the Swiss Light Source. Beam measurements proved that all specifications were met or exceeded [5] [6]. Furthermore the digitally controlled power supplies proved to be highly flexible and many features were added to increase the maintainability of this high number of power supplies far above the usual level.

The DPSCS is inherently a very flexible system. New features can be developed quickly on any prototype system and a fully automated distribution of the new software can then be used to reprogram all 576 power supplies within 15 minutes in order to provide the new feature. Even the regulation parameters of the different types of power supplies can be easily distributed. E.g. when we needed to set a group of quadrupole magnet power supplies to a value outside the originally specified stable minimum current, we were able to test the new configuration parameters at one power supply and then just copy the parameters to 11 others, instead of adjusting each one individually.

The 5 MHz optical fibre interface adds to the flexibility, since many fast feedback systems can directly control the device with a set point rate of up to 10kHz. This was a prerequisite for the fast orbit feedback [6] but it is useful for many applications like beam based alignment or energy ramping in the storage ring to speed up the measurements and increase their precision. It facilitates the fast reprogramming of the controllers via the control system, too.

Another outstanding feature is the ramp-on-demand of our 3Hz booster synchrotrons. Conventional boosters are powered by so called ‘white circuits’. They operate at a fixed frequency (10-50Hz) and the magnet current power is stored in a resonance circuit. Those boosters are typically operated one to three times a day for 20 minutes to refill the storage ring with electrons to compensate the unavoidable particle losses of the stored beam. At the SLS we want to keep the beam current stable to a percent level and need therefore to operate the booster about every three minutes for one to two seconds. Our digitally controlled booster dipole power supply with a 1 MW peak power is following a programmed set-point 3Hz sine wave from 24 to 840A. Within 10 cycles this wave reaches its full current. By starting the ramping 4 seconds before the actual refill, we operate it for 6 seconds within 3 minutes for the refill. This saves about 1.2 GWh of energy a year, compared to a conventional power supply running continuously.

The most important advantage for the easy maintainability of the 576 magnet power supplies of the SLS is the fact that all of them have an identical interface to the control system. The very specific requirements, like a 10kHz set-point rate, the ability to program arbitrary current waveforms or the feature to modulate the set current with a programmable frequency are featured by all 576 power supply controllers, even if they are just required by a small subset. This allows using the same hardware and software for all power supplies and reduces the maintenance work and the required investments on spare parts. The easy cabling with one duplex optical fibre cable and an optional simplex fibre trigger cable helps for a quick installation and a high flexibility on the cabling: even kilometre long cables could be used with single mode fibres, if required.

Many special features were added to the controllers to ease maintenance. E.g. the PS monitors the load resistance and alarms on deviations out of tolerance. Each controller gets an individual identifier number that allows to alarm swapped control cables. The ID is a combination from the 6-digit rack number and the location of the PS in the rack. Due to that the PS can even tell the operator where to find it. The readout of all the configuration parameters of the PS allows to detect any special configurations and to make sure that all PS are configured, as they should be. As mentioned above, it allows making an identical clone of any existing power supply, too.

The controller even eases the maintenance of the control system configuration for the power supplies, since they are “self describing”. The current range of the power supply is read by the control system from the controller and is used for alarm limits and provided to graphical user interfaces. All floating-point numbers are communicated as such, using the IEEE-754 standard. This alleviates from the need of conversion by the control system and eliminates therefore a very frequent source of errors. At boot time the control system reads the full status of the power supply and initializes itself to the state of the PS instead of initializing the PS. This increases the overall reliability of the accelerator: a failure of the control system causes no interruption of the beam for any static magnet power supply. The power supply controller provides its firmware version number to the control system and allows therefore to detect incompatibilities and to facilitate a version control.

The controller provides a total of 134 error codes, grouped in three categories. This allows a very quick failure analysis and therefore reduces the meantime to repair compared to conventional PS. The feature to report on errors that would prevent the power supply from being turned on proved to be very useful. Now we don’t need to switch on all PS after a machine shutdown to find out if some have to be repaired. This helped to reduce the average start-up time of the accelerator.

The power supplies are featuring an oscilloscope like analog interface, too. Each floating-point number of any controller registers can be assigned to any of the two DAC outputs. This was used in the early commissioning to check the performance and synchronisation of the ramped booster magnet power supplies. But the more the control system interface evolved, the less usage was made of this interface. »

Summary

The very positive experiences in the SLS and at PSI during the last five years of operation have confirmed the digital PS control technology: The flexibility of the system, combined with standardized hard- and software components, saves time and costs during engineering and operation. The simple and safe handling as well as the new features was appreciated by the users of the power supplies.

The potential of the digital control technology for particle accelerator power supplies is large and provides the capabilities for new and innovative applications. This technology will replace most conventional analog control in power supply applications in particle accelerators. The advantages of the digital control technology are proven now.

The digital power supply control system will be used in two accelerators in Europe and one in Asia. Other institutes are evaluating the system with experimental power supplies bought from PSI.

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