PRACTICAL EXPERIENCE WITH SELF-OPTIMIZING, HIGH DYNAMIC CONTROL OF ACCELERATOR MAGNET POWER SUPPLIES

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Abstract

In 1999, the first fully digitally controlled magnet power supplies were commissioned at PSI (Paul Scherrer Institute, Switzerland). Today, approximately 1000 of them are in use at PSI and a multiple of that worldwide. An extended PI structure is used for control. PI control is very effective and simple to use but the attainable dynamic performance is usually limited by the higher order characteristics of the output filter and the load.

For the future we expect increasing requirements from highly dynamic applications, such as beam orbit feedback systems and fast scanning magnets for proton irradiation of tumours. Therefore, a self-optimizing power supply control system was developed in collaboration with the University of Applied Sciences Northwestern Switzerland. It is based on the second generation of PSI digital power electronics controller, which allows more complex control algorithms and higher sampling rates.

This paper presents the achieved dynamic performance of the new control structure for various types of power supplies and magnets and compares them with the dynamic performance obtained using standard PI control.

INTRODUCTION

Comprehensive theoretical investigations for a high performance control structure resulted in a self-optimizing power supply control system (SOPS) [1] (Figure 1). It consists mainly of two parts – a state space controller combined with a PI controller (SS-PI) and an identification procedure. This allows the automatic determination of the state-space models for the power supply and the load as well as the calculation of the control parameters.

Subsequently, the SS-PI control structure was implemented on the second generation of PSI digital power supply controller DPC [2]. Thereafter, practical tests were conducted. The goals were to collect experience with different power supply types and magnets as well as to compare the performance with the standard PI control structure that is currently used at PSI [3] (Figure 2).

Three setups were investigated. Their properties are listed in Table 1:

- Corrector – part of a fast orbit feedback loop
- Aligner – no dynamic requirements
- Sweeper – used in proton tumor therapy [4]

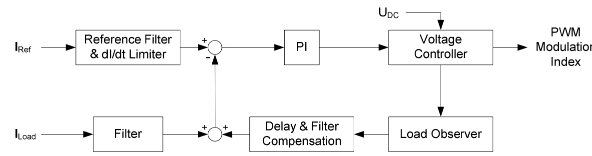


Figure 1: Simplified SS-PI controller block diagram.

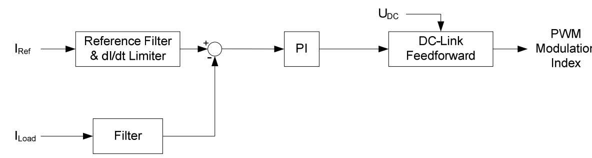


Figure 2: Simplified PI controller block diagram.

Table 1: Power Supply and Magnet Properties

Property	**Corrector**	**Aligner**	**Sweeper**
PS Current	±10A	±10A	±150A
PS Voltage	±12V	±12V	±200V
PWM Frequency	100kHz	100kHz	25kHz
Control Cycle	100kHz	100kHz	50kHz
Max di/dt	70A/s	145A/s	55000A/s
Switch Type	FET	FET	IGBT
Magnet Type	Laminated metal core	Massive iron core	Ferrite core
Magnet Impedance	1.3Ω, 50mH	225mΩ, 14mH	77mΩ, 2.2mH

EXPERIMENT SETUP

Control Parameters

Control Parameters for SS-PI are determined (semi-) automatically as described in [1]. The parameters for Standard PI are determined in a similar way and the proportional gain is then optimized manually. Identification is executed around $½I_{Nom}$ and the control parameters are chosen such that the step response is as fast as possible at this operating point without significant overshoot.

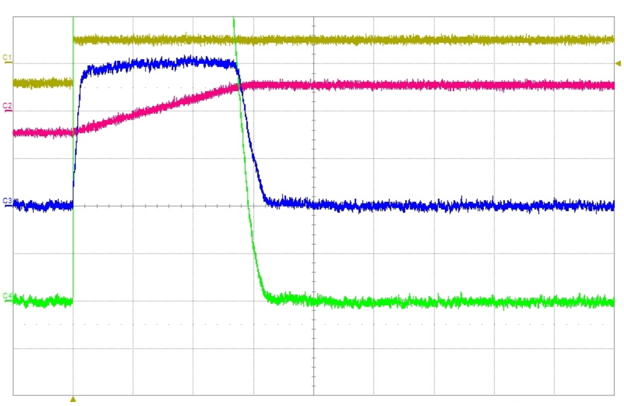
Performance Evaluation

For performance comparison, different step responses are measured at different operating points: A small step (≈2‰ of nominal current, I_{Nom}), a medium step (≈2%) and a full-scale step; operating Points are 0A, $½I_{Nom}$ and I_{Nom}.

Internal and measured signals such as the reference current, the measured magnet current and the calculated control errors are logged on the controller and/or displayed on an oscilloscope via digital-to-analog converters (DAC). For these measurements, the oscilloscope approach was used. An example is given in Figure 3.

Four signals are displayed on the oscilloscope; the time resolution is 500µs/div:

- The reference current (C1).
- The limited reference current, the current reference after the current limiter (C2)
- The ramp error, difference between the limited reference current and the measured current (C3)
- The control error, the difference between the reference current and the measured current (C4).



C1 (yellow):	Current Reference	100mA/div
C2 (red):	Limited Reference	100mA/div
C3 (blue):	Ramp Error	2mA/div
C4 (green):	Control Error	2mA/div

Figure 3: Example of a 100mA reference step, 500µs/div

Comparison Criteria

Criteria for the comparison are:

- Relative settling time – time until the control (or tracking) error is smaller than 2% of the step size;
- Absolute settling time – time until the control error is smaller than 500ppm of nominal current
- Overshoot
- Ramp error – tracking error while the reference current is limited by the di/dt limiter

The type of settling time criteria depends on the application. The relative criterion is used for the Corrector and the Aligner setup and the absolute criterion for the Sweeper.

RESULTS

The following tables compare the results obtained with the Standard PI and with the SS-PI control structure. The result on the left is with Standard PI and the result on the right is with SS-PI.

For better comparison, the theoretical ramp time (current step size divided by maximum di/dt), which is dictated by the di/dt limitation, is subtracted from the measured settling time to give the property 'adjusted settling time'.

Corrector

This corrector is mainly used to make fast and small corrections. The power supply shows excellent linear behaviour over the whole operating range and the magnet shows first-order behaviour. These are the ideal conditions for SS-PI.

Table 2: Corrector Comparison Results

Step [A]	Operating Point [A]	Ramp error [mA]		Adj. Settling Time [µs]	
		PI	SS-PI	PI	SS-PI
0.01	0	Not applicable (n.a.)		480	150
	$½I_{Nom}$			460	160
	I_{Nom}			480	160
0.1	0A	14	6	300	100
	$½I_{Nom}$	14	6	300	100
	I_{Nom}	14	6	300	100
10	0	14	6	n.a.	

Aligner

Even though this magnet was not designed for high-speed applications, it was an interesting test object to analyse the capabilities of the SS-PI control structure. The magnet has to be modelled with a fourth order model due to eddy currents caused by its massive iron core. Even then, the model does not sufficiently well model the magnet. Also, the low-frequency part of the filter model varied significantly among identification runs.

The common response of massive iron magnet to a current step is a fast jump to 60-90% of the final value followed by a very slow creeping to the final value. Experiments showed that even though SS-PI jumps closer to the final value and creeps faster than standard PI, it is evident that the control structure in its current form cannot significantly improve the behaviour for this type of load.

Sweeper

This special type of power supply is used for rapidly deflecting a proton beam to irradiate a three-dimensional target volume, a tumour. A beam position resolution of 0.1mm is required, this corresponds to a change in current of 100mA, and therefore, the absolute settling time criterion was used in this setup.

The dynamic behaviour of this power supply around 0A is severely compromised due to the nonlinearity caused by the deadtime of the switching elements. Therefore, both control structures are extended by a deadtime compensation (DTC) since both PI and SS-PI are not able to handle it sufficiently.

Table 3: Sweeper Comparison Results

Step [A]	Operating Point [A]	Ramp error [A]		Adj. Settling Time [µs]	
		PI	SS-PI	PI	SS-PI
2	0	n.a.		600	580
	½I_{Nom}			800	200
	I_{Nom}			800	260
10	0			1100	400
	½I_{Nom}			1100	520
	I_{Nom}			1000	500
300	0	12	7	1500	500

The SS-PI control structure showed some overshoot for the 0A operating point, 170mA for the 2A step and 250mA for the 10A step.

EXPERIENCE WITH SOPS

The Self-Optimizing Power Supply System (SOPS) allows achieving good results quickly. Some time had to be invested to learn which parameters to adjust to get even better results.

Accurate identification of the models is very important for the control performance. Therefore, it was necessary to learn how to interpret the results and to judge whether it was realistic. Identification works pretty well but was not always stable (Aligner). The length of the identification measurement (number of samples) influenced the results significantly.

Also important are the parameters of how many cycles of delay are compensated for identification and for control. Furthermore, the weighting coefficient that is used for the design of the LQR voltage controller has to be varied to obtain a sufficient damping of the output filter resonance without increasing the required pre-compensation too much.

PWM rounding, which is used to enhance the resolution of the PWM generator over several PWM periods, had to be switched off during identification because the resulting sub-harmonic oscillations, though small in amplitude, manifested in the identified voltage model as resonances.

PWM ripple also showed up as a resonance in case of the Sweeper. Thus, the ripple has to be filtered out prior to identification.

CONCLUSION

These experiments show that the SS-PI control structure gives a significant gain in dynamics for power supplies with linear and loads with first-order behaviour. In case of higher order loads, the structure would have to be expanded by an adequate loop-shaping. Since in particle accelerators, the main interest is in the dynamics of the magnetic field and the current is just an intermediary, massive iron core magnets with high requirements on dynamics are contradictory but it was an interesting test object to analyse the capabilities of the SS-PI control structure. The experiments with the Sweeper showed that the new control structure does not give a substantial advantage in case of non-linearities. These have to be compensated additionally. If the models correspond well with the real filter and load, a step response can be up to three times faster with the SS-PI control structure.

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