HIGH PRECISION MAGNET POWERING FOR THE SESAME STORAGE RING

S. Jafar, A. Ismail, I. Abid, SESAME, Amman, Jordan
M. Cerqueira Bastos, T. Henschel, CERN, Geneva, Switzerland
E. Onur Ari, TAEK, Ankara, Turkey
E. Yousefi, ILSF, Tehran, Iran

Abstract

SESAME is the first synchrotron light source for the Middle East, expected to start operation mid-2017. It is composed of a 22 MeV Microtron, a 0.8 GeV booster synchrotron and a 2.5 GeV storage ring. The storage ring magnets and power supplies were designed, procured, produced and validated under the framework of CESSAMag, a collaboration between SESAME and CERN supported by the European Commission. The power supplies are composed of a common control unit, a voltage source and a current transducer. In this paper, the powering strategy, choice, design and validation of the magnet power supplies are described as well as some of the challenges faced during the project. Finally, performance results are presented, showing stability of the dipole power supply at nominal current of about 10 parts per million.

POWERING STRATEGY

The initial powering strategy for the SESAME main ring foresaw series powering of the dipole and the quadrupole magnets. In addition, power supplies were to be bought as keys-in-hand systems. This strategy presented several risks, including the integration of third party controllers and the dependency on power supply manufacturers for repair and maintenance.

Table 1: Circuits and Current/Voltage Ratings

Magnet type	Circuit qty	Max current	Max Voltage
Dipole (DP)	1	550 A	800 V
Focusing Quadrupole (QF)	32	260 A	15 V
Defocusing Quadrupole (QD)	32	215 A	5 V
Focusing Sextupole (SF)	2	85 A	40 V
Defocusing Sextupole (SD)	2	125 A	60 V
Vertical Correctors (CV)	32	±10 A	±8 V
Horizontal Correctors (CH)	32	±10 A	±8 V
Skew Quads (SK)	8	±10 A	±8 V

An alternative strategy was proposed in which the power supplies are purchased as voltage sources to which a controller unit and a current transducer are added to form a high precision current source. In addition, the powering scheme was re-designed to include individual powering of the quadrupoles, increasing machine flexibility. The new strategy also includes the use of commercial, easy-to-replace, power supplies reducing Mean-Time-To-Repair (MTTR). The use of a single, SESAME selected, common controller for all power supplies, with SESAME designed interface electronics and control chassis, ensures easier integration and greater control over performance. Once the powering strategy was decided, the circuits were defined and the required power supply voltage ratings calculated. These are listed in Table 1 where it can be seen that 141 DC power supplies are required to power SESAME's main storage ring.

Control, Timing and Performance Requirements

SESAME's injector runs at 800 MeV while its storage ring runs at 2.5 GeV. To control the beam parameters of the storage ring, magnets must be ramped and driven in a reliable and reproducible manner, synchronized to better than 1ms. The main ring power supplies are ramped from about 30 % to 100 % of their nominal value in a few minutes. The uncertainty requirements for the current in the SESAME main ring magnets were discussed in [1].

These include the requirement for ±50 ppm short term stability for the dipole and focusing quadrupole current. In [2] these requirements were interpreted and extended resulting in the set of power converter performance parameters listed in Table 2.

Table 2: Power Supply Performance Requirements

Parameter	QF, DP	QD, SV, SH	CH, CV, SK
Offset error	10 ppm	10 ppm	10 ppm
Noise at Inom	25 ppm p-p	30 ppm p-p	40 ppm p-p
LF Noise at Inom	10 ppm p-p	15 ppm p-p	15 ppm p-p
Stability at Inom	20 ppm p-p	30 ppm p-p	80 ppm p-p
Gain error	10 ppm	20 ppm	20 ppm
Repeatability	5 ppm	10 ppm	20 ppm
Linearity	10 ppm	15 ppm	20 ppm

POWER SUPPLY DESIGN

Voltage Source

To satisfy the ratings in Table 2 power supplies from EEI, TDK-lambda and PSI were selected. For the quadrupoles and sextupoles, commercial off-the-shelf units from TDK-Lamda were selected. These power supplies are controlled by an analogue voltage. The dipole power supply was chosen from an existing design by EEI, Italy, in operation at Medaustron, Austria. This product was available in a short time with minor power requirement modifications to 440 kW and previous experience at CERN facilitated the integration with the SESAME controller. The power supply is controlled digitally via an RS422 link. Finally, the corrector power supplies were supplied by PSI (Paul Scherrer Institute) [3] which also supplies the power supply controller unit. One controller controls three corrector power supplies.

Power Converter Control Electronics

At the centre of the power converter control electronics is the power supply controller (PSC). The PSC reads the measurement from the current transducer and generates the voltage reference to be sent to the voltage source in order to produce an accurate current. In the case of the SESAME power supplies the regulation loop is implemented in the digital domain but the voltage reference can be either analogue or digital. This requires a high precision current transducer and ADC for the reading of the current and a DAC to generate an analogue voltage reference. After evaluating other candidates, the chosen PSC was the DPC unit from PSI [4]. The DPC consists of a controller card (DPC_CC) and, in the case of the dipole and focusing quadrupole power supplies, a high precision AD-converter (DPC_AD).

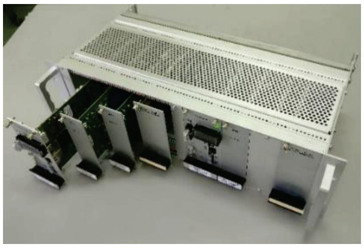

Figure 1: SESAME power supply control chassis.

The DPC_CC includes an FPGA which handles all the communication links and 12 independent, simultaneously sampling 16 bit AD converters (200 ksps). The PSC does not include a DAC, and for that reason, the DAC was included in a new board, designed by SESAME (SCE_IDAC), which also includes serial drivers for slow communication with the voltage sources, RS422 drivers for the dipole voltage reference, signal conditioning for the ADCs and the current sense resistor for the high precision current transducer (DCCT). A new backplane and control electronics chassis were designed to house two sets of control boards, in order to be able to control two converters per chassis. The chassis with the DPC_CC, DPC_AD and SCE_IDAC is shown in Fig. 1. A diagram of its integration in the control architecture (described in the next section) is shown in Fig. 2.

Control and Timing System Architecture

SESAME's control system consists of Graphical User Interface workstations (clients), Input/Output controllers, (gateways or servers), power supply controllers (PSCs), and a timing system. Clients and servers are developed using the Experimental Physics and Industrial Control System (EPICS) toolkit. EPICS servers are implemented as EPICS Input/Output Controllers (IOC) running on Linux based PowerPC platforms hosted inside 1U VME crates. Gateways relay commands from the clients to the PSCs, and report back process variables. Each gateway controls up to 16 PSCs. There are a total of 6 gateways controlling a total of 93 PSCs. Gateways communicate with clients over a Gigabit Ethernet network, and communicate with PSCs over point-to-point optical fibre links. An event-based timing system serves as the timing reference for the entire control network. An event generator distributes trigger and synchronisation events to the gateways. The gateways relay trigger events to the PSCs to synchronize waveform sequencing across all power supplies. The event generator produces two periodic events: synchronization and trigger.

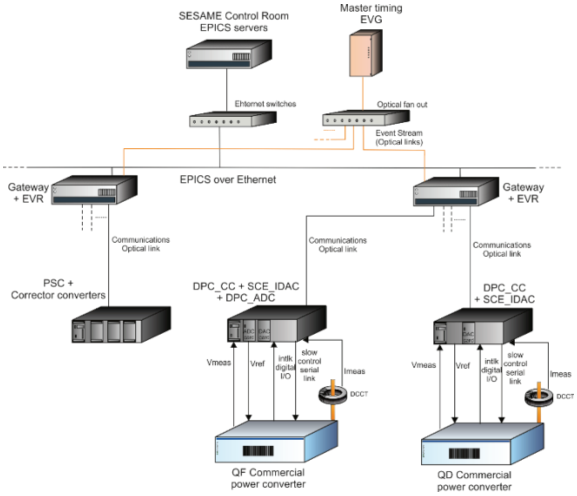

Figure 2: Control and timing system architecture.

The gateway contains an event receiver (EVR) which receives the events, converts them to signals, and distributes the signals to all PSCs over an optical network. The synchronization event is a synchronous master clock reference used by the PSCs to synchronize their clocks. The trigger event is an asynchronous signal used by the PSCs to synchronize each other's' outputs. Upon reception of the trigger signal, the PSCs drive their loads with pre-loaded current waveforms. At each received event, the EVR maps it to a pulse on the rear connector. The pulses are read by an FPGA on the gateway which communicates with up to 16 PSCs over an optical fanout by transmitting packets at the rate of 100 kilo packets per second

Control Firmware

The power supply firmware architecture consists of a cooperative real-time operating system that schedules a set of tasks and interrupt handlers. Current regulation is achieved via a digital PI controller. The architecture of the current regulation is shown in Fig. 3. The power supplies can operate in one of the following states: Off, Standby, DC, Waveform, Openloop, and Interlock. In DC mode, the power supply outputs are enabled, closed loop current control is enabled, and the power supply receives DC current references. In Waveform mode, the power supply is able to cycle through current waveforms stored in non-volatile memory. Waveforms are stored as normalized values with an associated peak value. The corresponding gain is automatically calculated by the controller. This enables the machine physicists to easily fine tune the ramping on the fly without needing to upload new waveforms with every modification on the output current values. The power supply plays up to four of those waveforms, in a configurable sequence.

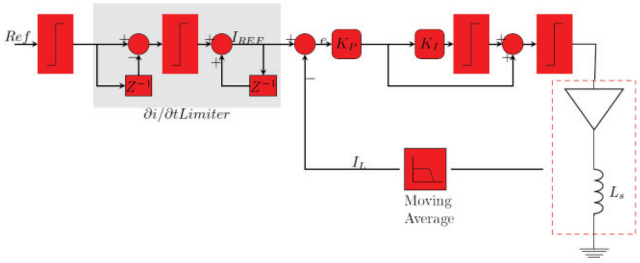

Figure 3: Architecture of the current regulation.

In Waveform mode, the power supply waits for a trigger event before it starts to play the next waveform in the sequence. Trigger events can be manual or automatic. Trigger events are sent to the power supply via the timing system over optical fibre. In Openloop mode, open loop voltage control is enabled and the power supply is able to receive voltage references instead of current. The power supply continuously monitors a number of interlock sources. At all times, the power supply keeps a running log of the last 10s of seconds of certain process variables such as load voltage and load current. Upon detecting an interlock condition, the power supply logs a few more seconds past the interlock then stops logging. The log can then be dumped in order to help in postmortem analysis.

POWER SUPPLY TESTS AND RESULTS

Factory Acceptance Tests (FATs)

The Dipole Power Supply was adapted to the SESAME application from an existing power supply design for MEDAUSTRON. To validate it, a series of FATs were carried out during which some issues were identified and corrective actions applied. These included: reduction of bus bar loop surfaces to improve immunity, integration of a thermostat on the brake chopper and on the crowbar circuits, moving the DCCT chassis away from EMI sources and hot spots, adding EMC capacitors on the output filter.

Integration and Performance Tests

Upon their arrival at CERN the quadrupole, sextupole and corrector power supplies were integrated into 19 inch racks with the control system, power distribution, interlocks and ventilation. Testbeds were prepared for all power supply types. The testbeds included a suitable load and reference DCCTs to measure the output current. Functional and performance tests were carried out in all individual power supplies. Performance tests included calibration, stability, noise, repeatability and linearity. In Table 3, a summary of the results obtained during the performance tests of the Dipole power supply is presented. In addition to performance tests, a tracking test was carried out using the dipole power supply running on a 92.5 mH, 154 mΩ load and a focusing quadrupole power supply running on a 3 mH, 11 mΩ power supply. The two power supplies were ramped together from 0 A to 60 A and the tracking error was measured. The synchronized measurement of the two currents was made using 2 STACC LHC 600 A DCCTs, read by two HP3458 DMMs synchronously triggered by a 33220A Agilent function generator which produces trigger pulses at the desired acquisition rate. The function generator is triggered by a start of ramp pulse sent by the timing system. The DMMs are synchronised to better than 1us. The DCCTs are the same model and have similar responses. Several tests were performed, using different bandwidths on the power supply control. For the worst case, the average measured value of the error for the linear part of the ramp during this test was -8 ppm (of 600 A) at a ramp rate of 6 A/s. That yields a delay of 800 µs, which, considering the system's calibration uncertainty estimated at ±5 ppm, gives: 800 µs ± 200 µs.

Table 3: Summary of Performance Results for Dipole PS

Parameter	**Required**	**Measured**
Offset error	10ppm	7 ppm
Noise at Inom	25ppm p-p	21 ppm p-p (extrapolated for final load)
LF Noise at Inom	10ppm p-p	5 ppm p-p
Stability at Inom	20ppm p-p	18 ppm p-p
Gain error	10ppm	-6 ppm
Repeatability	5ppm	6 ppm
Linearity	10ppm	6 ppm

Commissioning Tests

Once the power supplies were installed at SESAME, commissioning tests were carried out. Functional tests were carried out in all systems and performance tests carried out in one dipole and one quadrupole system. A 6 h heat run at nominal, with measurement of current stability via an external reference DCCT, was carried out. Drift during 6h was <20 ppm for the quadrupole and <12 ppm for the dipole. Other parameters were also checked, such as maximum regulation error and noise, with satisfactory results.

CONCLUSION

A complete powering system for the SESAME main ring magnets was successfully designed, procured/produced, evaluated and commissioned. Stability of the magnet current is proven to be better than 12 ppm for the Dipole power supply and better than 20 ppm for the Quadrupole power supply during a 6 h run. Power supply commissioning is presently finished and beam has already circulated in the machine. SESAME is foreseen to start physics mid-2017.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support of the European Commission via the FP7 CESSAMag project, and the additional support of the European Organization for Nuclear Research, the International Atomic Energy Agency, the Iranian Light Source Facility and the Turkish Atomic Energy Commission.

REFERENCES

[1] M. Attal, E. Huttel, K. Maukyan, *Optics-limitation*, SESAME note ref. SES.TE.MP.SPC.140418, 04/2014

[2] M. Cerqueira Bastos, Considerations about SESAME power converter accuracy requirements, CESSAMag internal note, April 2016

[3] R. Künzi *et al.*, "Bipolar 10 A and 50 A Magnet Power Supplies for SWISSFEL", IPAC'13, ShangHai, China

[4] M. Emmenegger *et al.*, "A New Generation of Digital Power Supply Controllers", in Conf. Proc. C100523 (2010) WEPD071, IPAC-2010