

Considerations in Designing Power Supplies for Particle Accelerators

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Abstract — Stringent demands must be fulfilled when designing power supplies (PSs) for particle accelerators, such as stability, efficiency, accuracy, and electromagnetic compatibility. In this context, the paper analyzes the basic requirements to be considered when designing a PS for such applications. After reviewing the main circuitry topologies used in PSs, the electrical specifications and functional modes necessary to set up high-performance PSs are addressed. Problems concerning the fulfillment of the electrical specifications are discussed, followed by an overview of the common PS control methods. Finally, the impact of some of the discussed design considerations is evaluated for the PS of the magnets of particle accelerators.

Keywords — Particle accelerator, power supply, efficiency, reliability, EMI filter, control system.

I. INTRODUCTION

Various fields of applications such as medical instrumentation, aero-space, deep sea exploration, and complex particle-physics facilities like the Large Hadron Collider require highly accurate, stable and reliable Power Supplies (PSs) for the embedded equipment to avoid any mishandling of delicate activities or expensive experiments [1]. Particularly in the design and control of PSs feeding the magnets of particle accelerators [2,3], the main demands to be fulfilled are high accuracy in current tracking (due to the requirements on the magnetic fields) and power factor close to the unit (due to high power involved) [4-6]. Nowadays, the most often used topologies of PSs operate in switching mode (SM) because it allows a better usage of the magnetic components and results in higher efficiency; however in some applications the linear PSs are still used [7,8]. Switching mode power supplies (SMPSs) came into being spurred in the early 70's due to the huge development in switching semiconductor devices and more recently to the appearance of new semiconductor technologies such as the silicon carbide (SiC) and the gallium nitride (GaN) [9].

While in the past, the major performance improvements made in PSs had been brought by refinements in power converter topologies and advances in semiconductors and magnetic materials, the present and next improvements in PSs are expected to come mostly from system architecture, power management optimization, and advances in packaging and thermal management techniques. This means that research and development on PSs are shifting from the converter-level

topology to the system-level architecture and load-activity-based power management [10]. Furthermore, safety issues must be considered in the design of PSs to prevent any hazard to human beings. From the composite situation delineated above, it turns out that a large collection of design standards and certification processes must be taken into account by the PS designers, thus increasing their responsibilities in meeting specifications for the PSs.

II. TOPOLOGIES

Research efforts on PSs have been focused on finding topologies that offer improved conversion efficiencies and power densities. Fig. 1 shows the topologies of DC-DC PSs; they can be divided into three main technologies according to the operation mode: 1) linear, 2) switching and 3) soft-switching or resonant.

A. Linear and switching technologies

Linear technology has advantages of simplicity, low noise, fast response time, and excellent regulation. Its disadvantage is concerning with the low efficiency as it dissipates power in any working condition.

Instead, switching technology allows the opportunity to significantly reduce both the size of magnetic parts and the conduction losses of the semiconductor devices.

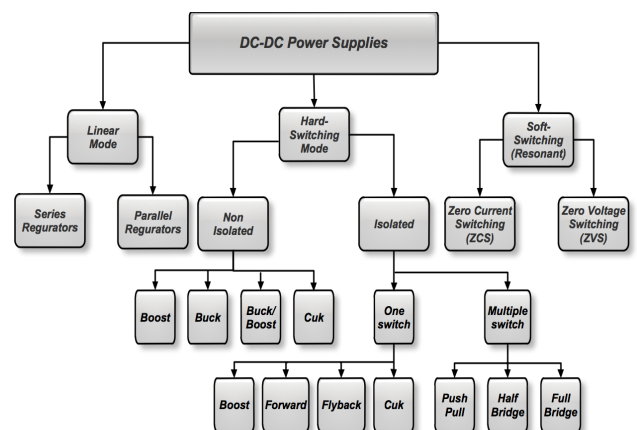


Fig. 1. Topologies for DC-DC power supplies.

Advantages of SMPSs are as follows: loss reduction, higher efficiency, attenuation of harmonics in the range of tens of kHz, smaller filter size and output transformer built up with lighter ferrite cores. Disadvantages are the increased control complexity, the upsurge of EMI and RFI problems, and the cost.

B. Soft-switching or resonant technology

In the switching technology the finite duration of the switching transitions will cause high peak pulse of power dissipation in the devices, degradation of the converter efficiency and possible damage of the transistors during the turn-off transition. By help of load-line snubbers, these inconveniences can be mitigated since the snubbers lessen the stresses on the switches, as shown in Fig. 2. A more effective solution in reducing the switching losses consists in the use of resonant power conversion and has led to the development of families of resonant converters like the zero-current-switching (ZCS), zero-voltage-switching (ZVS), quasi-resonant (QR) and multi-resonant converters (MR), as well as the class-E converters [11,12]. Nowadays, the extremely challenging requirements for simultaneous maximization of the efficiency over the entire load-range efficiency and the power density direct the optimization efforts of the PSs towards the development of topologies that can operate at significantly high switching frequencies while achieving high efficiencies.

III. SPECS AND MODES

When designing a power supply for any application, it is necessary to know the output voltage and current demands for the product as well as the electrical and physical environment that the equipment will operate in. Moreover, it is necessary to know its functional modes. Main electrical-related specs and modes are listed in Table I.

A. Ripple and noise

Ripple and noise are traditionally the first items to look at. They are important because the first choice to be done is between linear or switching mode or hybrid PS. The linear PS has low ripple and noise and, furthermore, exhibits fast transient behaviors. However, it is inefficient due to the high power dissipation that becomes larger and larger with the PS power and is therefore convenient only at low output power levels (<500 W).

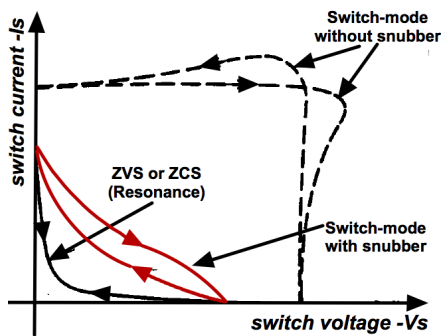


Fig. 2. Switching loci trajectories.

TABLE I. ELECTRICAL SPECS AND FUNCTIONAL MODES

Parameter	Unit
Input Voltage DC-Link	VDC
Max/Min Output Voltage	V
Max/Min Output Current	A
Output current ripple and noise	μA_{RMS}
Transient response	s
Output current stability	μA_{RMS}
Slew rate	V/s
Switching frequency	kHz
Efficiency (full load)	%
Operation mode	Manual/Remote
Configuration mode	Series/Parallel
Control mode	Analog/Digital

B. Transient response

The transient response indicates how fast the PS can follow the impedance changes of the load or how it copes with fast changes in the load current. When the load current changes rapidly over a large range, the output voltage will decrease or increase significantly for a short period of time. Immediately, a built-up voltage control loop will try to recover the output to its set voltage. In the PSs there is a trade-off between the features of the bandwidth of the voltage control loop and the output filter. A large output filter cut-off frequency limits the output ripple but makes the supply slower to react to fast changing loads.

C. Stability

The stability specifies the long-term drift of output voltage and current. Regarding the long-term stability, once defined a specific set value, PSs should stay as close as possible to that value over a long period of time. A typical application is in energizing the magnets of particle accelerators, where the PSs work as current source in constant current mode for long periods of time (hours or days). In this application what really matters is to ensure that the established magnetic flux drives the particles accurately; therefore the DC output current must remain at exactly the set-point value during all the time length of the experiment.

D. Slew-rate

The slew-rate specifies rise and fall times for the DC output voltage. As mentioned before, to improve the ripple and noise specifications, the PSs usually have output filters with large capacitors and, consequently, a lot of stored energy. It is mainly the charge and discharge times of these capacitors,

combined with the current demand, that determine the DC output voltage slew-rate.

E. Output voltage and current regulation

Similarly to the slew-rate, the load regulation exerts a permanent control of the output voltage and current. Output voltage moves from its set-point in response to variations in the output current. However, this effect is normally very small (less than 0.01% of the settled output voltage). Only when the internal impedance of the PS is high the load regulation takes unacceptable values.

F. Efficiency

Efficiency of PSs depends on their topology and control mode. As referred in Section IIA, linear technology does not offer a significant chance of reducing size and weight of the PS components, and PS efficiency is determined by the ratio of the output and input voltage. On the other hand, switching technology produces a significant reduction in size and weight of the PSs and allows a reduction of heat sinks and magnetic parts compared to the linear technology. Therefore efficiency of the SMPSs is typically higher. PS efficiency affects directly the upper limit of the power supplied to its output for a given package size and cooling mode. This rule is very important in the design of a PS, since there is almost always an effort toward size reduction and miniaturization of electronics products, PSs included.

G. Configuration and operation modes

Parallel output configuration of PSs is generally adopted when high output current is required. The advantage of this dedicated configuration is that the total performance of the units operating in parallel still meets the original specifications of just one single power supply. Normally the system defines automatically which unit is the master and which units are the slaves. When placed in parallel, multiple PSs may come with different current ranges but should have the same output voltage range. In this case the total current is the sum of the currents delivered by each PS. In series configuration, multiple PSs are placed in a totem fashion by connecting the positive pole of one supply to the negative one of the other supply, with each PS that must be isolated. Then both negative and positive poles must be floating, and isolated PS interfaces must be used of either analog type or digital type like RS-232, RS-485 or Ethernet. When placed in series, there is no master/slave concept and each PS is programmed individually.

H. Control mode

Concerning the control of the PSs, it can be 1) full analog, 2) part analog and part digital or hybrid, and 3) full digital. The digital control [13, 14] offers several advantages such as flexibility, easy configuration and reconfiguration of the system by firmware, which can be used to scale the size of memory and storage space (adaptation capability). Firmware can be made self-tuning in time, which calls for the implementation of non-linear control algorithms. Some of the control signals needed to remote operation of a PS, independently of its type, are listed in Table II. They are divided into three main categories that are: Monitoring and interlock, Hardware protections and External interlock signals.

TABLE II. CONTROL SIGNALS

Type of Control	Signals
Monitoring and interlock	Input under voltage Input overcurrent Output overvoltage
Hardware protections	Input overcurrent MOSFET failure Input fuse
External interlock signals	PS status (On/Off) Fault Reset Voltage set Voltage/ Current monitoring MOSFET On/Off

I. Transformers and inductors

The magnetic components are the cornerstone for a SMPS designer and also the less understood subject. A suitable design of the magnetic components gives a key contribution to the reliability of the PSs. Two situations can arise from a poor transformer design: 1) high voltage spikes, and 2) possibility of core saturation. Regarding the selection of the core type, the window configuration is extremely important at higher frequencies, typically in resonant configurations. A core with the maximum window width, which minimizes the number of layers resulting in a lower leakage inductance, is the best option.

J. Components and materials

Advances in semiconductor technology have always been the major thrust behind efficiency and power density improvements in power conversion circuits. Specifically, improvements in PS performance have been achieved in the past decade mainly thanks to the extraordinary reduction of the on-resistance of high-voltage MOSFETs and equally impressive enhancement in reverse-recovery characteristics of high voltage silicon (Si) rectifiers.

Forthcoming major improvements in high-voltage, high-frequency semiconductor components are expected to come from the silicon carbide (SiC) and the gallium nitride (GaN) technology. Their superior electrical characteristics make them candidates to replace Si. In particular, the recently introduced high-voltage SiC Schottky rectifiers have already demonstrated to outperform Si rectifiers in high frequency applications. Gallium nitride, in turn, has both a wider band-gap and higher electron mobility than Si, which enable the development of high-voltage, high-frequency devices, raising the figure of merit of the next generation of power converters [15].

K. Input line disturbances

In most industrial environments PSs are fed by an AC line that is far to be clean. This because the PSs share the line with other equipment, often non-linear or time-variant, that can absorb a large power. Therefore, disturbances such as sags and surges are frequent.

L. Electromagnetic interferences-EMI

Typical filters employed to suppress EMI include common mode and differential mode inductors. Common mode noises are high-frequency noises in phase each other, having circuit paths through ground as closing ways. The common mode

inductors offer high impedance to this noise, absorbing it and then dumping it to ground through low impedance capacitors.

IV. CONTROL METHODS

On account of the large number of existing solutions for the control of the PSs, examples of the most common control methodologies [16], as summarized in Fig. 3, are presented.

A. PID control

Over 85% of all dynamic controllers are of PID type with a great variety of forms and design methods for the PID parameters.

B. Voltage control

The voltage is measured at the PS output and is compared with a reference or set-point to generate an error signal. This signal is applied to the input of a compensation PID-type block. In this control mode any change in the source or the load is detected only after it has propagated to the output.

C. Current control

In current control an inductor current is used as a feedback state [12]. However current and voltage reference values are not independent and they specifically require knowledge of the load. To overcome this obstacle, two loops of control are normally arranged, the outer loop manages the output voltage error by generating the necessary current reference whilst the inner loop makes the converter to act as a current source.

D. Adaptive control

Adaptive control is used when the parameters of the plant dynamics are unknown and/or change in time. Adaptive control covers a set of techniques, which provide a systematic approach for automatic adjustment of the control signal or parameters in real time, in order to achieve or to maintain a desired level of the system performance.

E. Variable frequency control

By this control, a voltage-controlled oscillator (VCO) triggers the switches of the converter with pulses of fixed length but of variable frequency. The operating frequency is adapted to the conditions required by the load.

F. Optimal control

The optimal control, also known as linear quadratic regulator (LQR), has some advantages compared to the classic control because the designer needs only to guess the values of several parameters. Usually, the energy function of the resonant circuitry is minimized and hence the transient response is optimized. The significant merit of the LQR is that a robust control with quite good accuracy margins is guaranteed when the state variables are accessible. The design procedure starts with the calculation of the linear state-space model of the circuit at one operating point.

V. PS IN PARTICLE ACCELERATORS

The PS of the two synchrotron light sources operating in the Italian “Elettra Sincrotrone Trieste” Research Center, namely Elettra, the 3rd-generation source, and FERMI, the 4th-generation one, are here presented, comparing their performance.

A. Description of the Elettra Facility

The electrons circulating in the Elettra’s 260-meter long Storage Ring (SR) at nearly the speed of light provide ultra-bright radiation in the infrared to hard x-rays spectral range when passing through different magnetic devices such as undulators, wigglers and bending magnets. The photon beams, collected by in-vacuum optical systems, propagate through beamlines and reach the experimental stations where arrays of different analytical and processing techniques are available. Fig. 4 shows the circular building hosting the Storage Ring and the photon beamlines of Elettra.

B. Elettra Magnet PSs

The electrons are first generated and accelerated by a linear accelerator and a booster synchrotron (the smaller buildings inside the bigger “torus”). Then they are injected into the storage ring, where they circulate at constant energy and current for several days in a row.

In order to keep the electron bunches on the predefined trajectories, a large number (~350) of DC and low-frequency (<3 Hz) AC magnet PSs are required, with currents ranging from 1 A up to 2000 A. Fig. 5 shows a typical PS block diagram. The power circuit converts incoming AC power to the form required by the magnet load, which is usually DC.

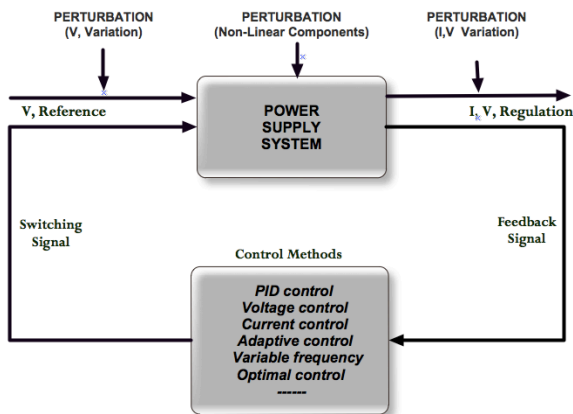


Fig. 3. Control methods for PSs.



Fig. 4. - Aerial view of the building hosting Elettra Storage Ring (SR).

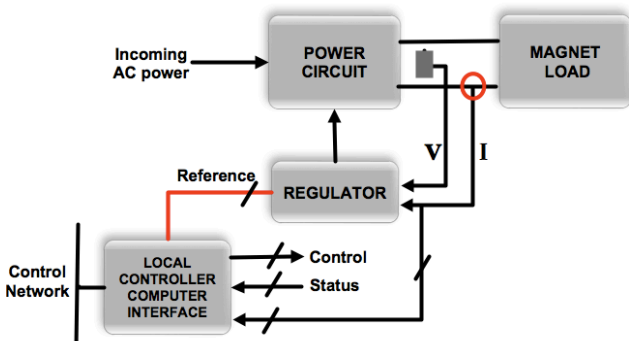


Fig. 5. Generic Accelerator Magnet PS.

The PSs of the SR magnets are interfaced to the local computer by means of industrial standard VME crates installed inside the cabinets and are equipped with CPU and a serial interface to the remote control of the system. Moreover, for each PS, a 16-bit DAC, a 16-bit ADC, and a limited number of digital I/O channels are available. In the Booster, the interface is based on a standard developed at the Paul Scherrer Institut in Switzerland and adopted by other accelerators in Europe [17].

C. Description of the FERMI Facility

The FERMI facility (total length: ~360 m) consists of a linear accelerator, two chains of “undulators” (arrays of permanent magnets that generate the free-electron laser (FEL) effect) operated alternatively and a “front end” connected to the beamlines in the Experimental Hall (Fig. 6).

About 400 magnet PSs ranging from 5 A to 750 A are used to drive the electron bunches along the accelerator and the FEL structure [18]. All PSs are remotely controlled via Ethernet.

Bipolar PSs (5 A and 20 A output current) were especially designed by the Elettra staff for supplying some types of magnets on FERMI. Some details on the 20 A unit are reported in the next subsection.

D. Description of the A2620BS Power Supply

About 200 A2620BS (± 20 A; ± 20 V) PS units are installed in FERMI and are designed to operate with short interruptions for 6000 h/year. Stability, reliability and efficiency are key factors for these PSs. The A2620BS is fully digital: a DSP implements a PID control and generates a high resolution Digital Pulse Width Modulation - DPWM (19 bit) based on a proprietary procedure, and another DSP is used for diagnostics, communication and handling interlocks (e.g. magnet fault, over temperature, overvoltage). The block diagrams of the A2620BS are reported in Figs. 7 and 8.

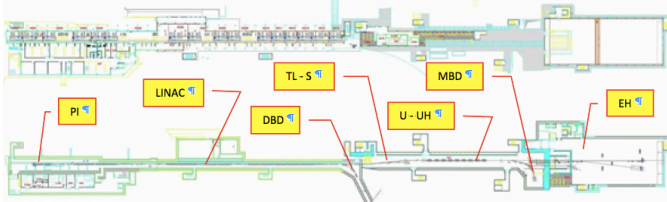


Fig. 6. FERMI general overview.

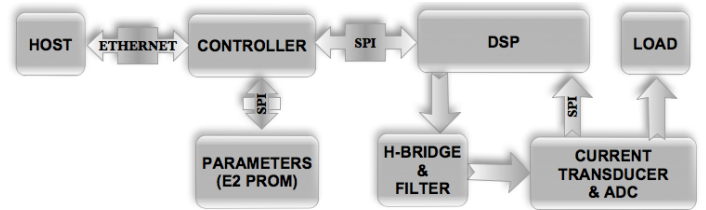


Fig. 7. Functional Block diagram of the A2620BS.

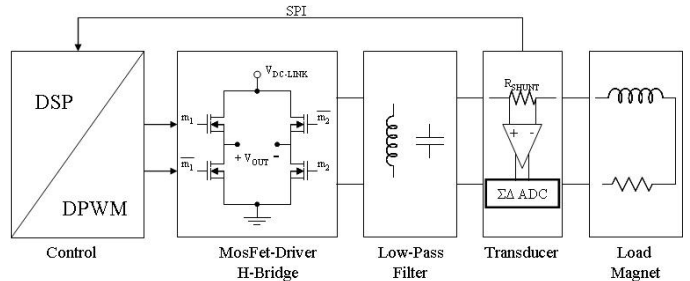


Fig. 8. Block diagram of the A2620BS

VI. EXPERIMENTAL RESULTS

The performance, as obtained from experimental results, of some PSs installed at Elettra and FERMI are presented. One of the most critical parameters of a magnet PS is the stability in time of the output current, set at a constant value.

A. Elettra Storage Ring

In Figs. 9 and 10 two stability plots from a quadrupole magnet PS are shown. In Fig. 9 the reference, provided from the 16-bit DAC to the analog regulation circuitry, is compared with the actual output current read-back and sent to the ADC. The maximum current of the PS is 300 A. The data were acquired during normal operations of the PS over about 4 hours.

The output current of another quadrupole PS operating in the SR is monitored for more than 7 hours. The data, which have been acquired during normal operation of the PS, are presented in Fig. 10. As it can be observed, the transient response is performed in two steps and, even facing with a change in current, the stability of the PS system is always achieved. The PS is then set to 0 A and off. Fig. 10 also shows that there is practically no output ripple and noise in this PS.

B. FERMI

The stability tests of some PSs of FERMI are shown in Figs. 11 and 12. Fig. 11 reports a 10-hour test at full current for an A2620BS and Fig. 12 shows similar tests for a custom dipole PS [19]. Observing the tests made in the Main Beam Dump (MBD) area of FERMI it appears that the stability is always achieved. Another important aspect to point out is related to the output ripple, which is very low.

VII. CONCLUSIONS

An overview of the technologies and topologies to consider when designing PSs for particle accelerators has been presented in this paper. The electrical specifications and functional modes required in the design were also considered, followed by an overview of common control methods used in PSs.

The impact of some design considerations on the PS performance has been evaluated in two facilities of a synchrotron light source, namely the 3rd-generation source, Elettra, and the 4th-generation source, FERMI, of the Italian Research Center “Elettra Sincrotrone Trieste”. Experimental results obtained for the two cases showed a very good stability, reliability as well as low output ripple of current and good transient response, with efficiency of 95%.

REFERENCES

- [1] Ying, J., "High Efficiency Power Supply Technologies", in IEEE - 7th International Power Electronics and Motion Control Conference. Harbin, China. pp. 1550 – 1554, 2012.
- [2] S. Jang, H. J.Ryoo, S. Ahn, J. Kim, G. Rim, "Development and Optimization of High-Voltage Power Supply System for Industrial Magnetron". *IEEE Trans. on Ind. Elec.* 59(3): pp. 1453 – 1461, 2012.
- [3] K. Li, J.Liu, G. Xiao, Z. Wang, "Novel Load Ripple Voltage-Controlled Parallel DC Active Power Filters for High Performance Magnet Power Supplies". *IEEE Trans. on Nuclear Sci.* 53(3): pp. 1530 – 1539, 2006.
- [4] The Candle web site: <http://www.candle.am>
- [5] The Diamond web site: <http://www.diamond.ac.uk/>
- [6] The Elettra web site: <http://www.elettra.eu/>
- [7] J.A.M. Ramos, A.M. Pernia, J. Diaz, F. Nuno, and J.A. Martinez, "Power supply for a high-voltage application," *IEEE Trans. on Power Electronics*, vol. 23, no. 4, pp. 1608–1619, Jul. 2008.
- [8] N. Marks, "Power supplies and accelerators", Proc. of CERN Accelerator School on 'Power Converters for Particle Accelerators', Warrington, UK, 2004.
- [9] W. Saito, I. Omura, T. Domon, K. Tsuda, "High Voltage and High Switching Frequency Power-Supplies using a GaN-HEMT". in Compound Semiconductor Integrated Circuit Symposium. 2006. San Antonio, TX, USA.
- [10] F. Lenkszus, "State of the Art Developments in Accelerator Controls at the Advanced Photon Source," Proc. PAC 1999, pp. 333-337.
- [11] N. Shafei, M. Pahlevaninezhad, H. Farzanehfard, A. Bakhshai, P. Jain, "Analysis of a Fifth-Order Resonant Converter for High-Voltage DC Power Supplies," *IEEE Trans. on Pow. Elec.*, vol. 28, pp. 85-100, 2013.
- [12] J T. Ching, K. Chan, "Review of Soft-Switching Techniques for High-Frequency Switched-Mode Power Converters", IEEE Vehicle Power and Propulsion Conference (VPPC), Harbin, China, 2008.
- [13] C. Rossi, A. Tilli, M. Toniato, "Digital Control of High Performance Power Supplies for a Synchrotron Light Source," in Advances in Control Theory and Applications, Springer, 2007, pp. 213-237.
- [14] D. Hamza, M. Pahlevaninezhad, P. Jain, "Implementation of a Novel Digital Active EMI Technique in a DSP-Based DC-DC Digital Controller Used in Electric Vehicle (EV)," *IEEE Trans. on Power Electronics*, vol. 28, pp. 3126-3137, 2013.
- [15] GaN Based Power Devices: Cost-Effective Revolutionary Performance. Available at: <http://www.irf.com/pressroom/>
- [16] N. Mohan, T. Undeland, Power Electronics, Converters Applications and Design. New York: John Wiley and Sons, Inc., 2003.
- [17] R. Visintini, D. Molaro, "Elettra booster magnet power supplies: one year of operations", Proc. PAC 2009, Vancouver, Canada, TU6RFP019.
- [18] R. Visintini, M. Cautero, D. Molaro, "Magnet power supplies for FERMI@Elettra", Proc. PAC 2009, Vancouver, Canada, TU6RFP020.
- [19] R. Visintini et al., "Power supplies for the diagnostic and main beam dumps of FERMI@Elettra", Proc. EPE 2011, Birmingham, UK, article code 0155.

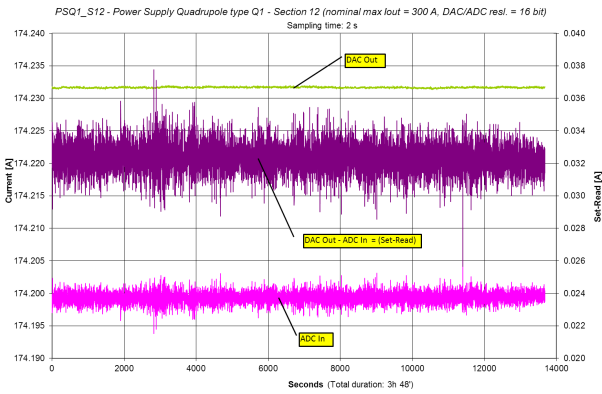


Fig. 9. Stability test: DAC reference vs. output current.

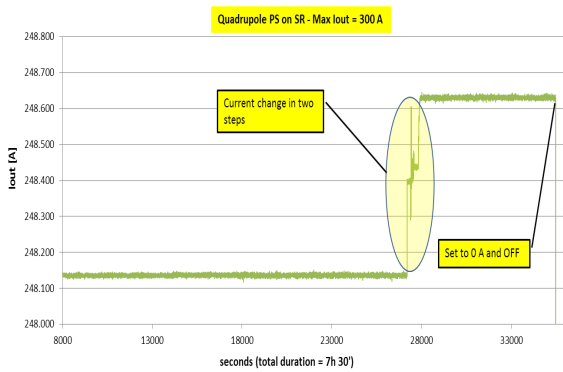


Fig. 10. Output current stability and set variation.

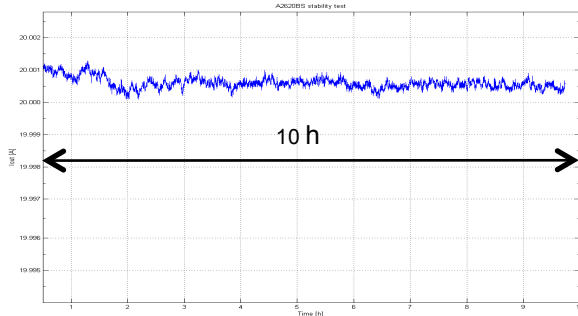


Fig. 11. A2620BS 10-hour stability test at full current (20 A).

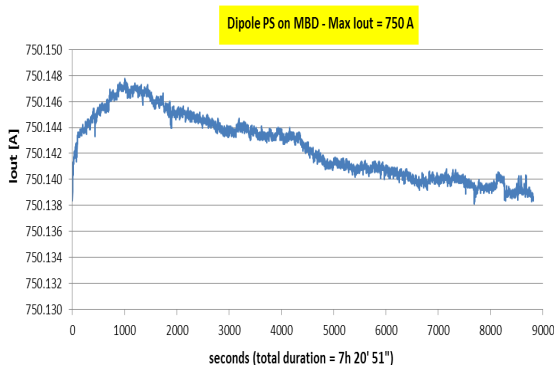


Fig. 12. Stability of a custom dipole PS in the MBD (full current).