Different power supplies for different machines

Hans-Jörg Eckoldt
DESY
Warrington, UK
17.05.04
Different Power Supplies for different machines

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Congratulation for having chosen

POWER ELECTRONICS
Power electronics needs the knowledge of

- Power electronic devices
- Mains behavior
- Regulation theory
- High precision measurement
- Mechanical capabilities
- Analog circuit technology
- Digital circuit technology
- Control system
- Statistics for large number of systems
- Databases
- Cooling technology
- Programming e.g. Internet, FPGAs, DSPs, PLCs
- Simulation tools
  - Missing RF, but with switched mode power supplies we are working on this
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Sorry!

• Please be not disappointed, if your very interesting power supply is not mentioned here

• Due to the large number it is not possible
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Structure of the seminar

• Cycling machines
• Fast ramping machines
• Slow ramping machines
• Pulsed machines
  – Magnet Power Supply
  – Constant power power supply
Cycling Machines

- DESY II, Hamburg
- ESRF, Grenoble
- BESSY II; Berlin
- SLS, Villingen

- Operation at frequencies between 0.3 and some 10 Hz
- Special care has to be taken for the flicker frequencies
Disturbances to the mains

The amount of allowed disturbances is defined in the German standard VDE 0838, IEC 38 or the equivalent European standard EN 61000.

No energy consumer is allowed to produce more distortions than 3% of the voltage variation of the mains.

For low frequencies in the visual spectrum this value is even more restricted. The low frequencies are called flicker frequencies. The human eye is very sensitive to changes in light intensities in this frequency domain.
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Allowed disturbancies to the grid according to IEC 38/VDE 0838

Bild 5-2: Verträglichkeitspegel für regelmäßige rechteckförmige Spannungsänderungen
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White circuit

AC POWER SUPPLY

WHITE CHOKE

DC POWER SUPPLY

CAP BANKS

16 MAGNETS
+ 1 MAGNET ON REFERENCE GIRDER
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Calculated Power with and without White circuit for BESSY II

- Direct dipole powering without White circuit
- Dipole powering via White circuit

Power consumption vs. time
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DESY II
4.5 GeV, 7 GeV, 10 GeV max.

<table>
<thead>
<tr>
<th></th>
<th>Dipole</th>
<th>QP</th>
<th>SP</th>
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<tr>
<td>$I_{\text{max}}$</td>
<td>1170 A</td>
<td>1530 A</td>
<td>530 A</td>
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<tr>
<td>$I_{\text{rms magnet}}$</td>
<td>873 A</td>
<td>940 A</td>
<td>324 A</td>
</tr>
<tr>
<td>$U_{\text{rms Choke/magnet}}$</td>
<td>4.3 kV * 12</td>
<td>3.34 kV</td>
<td>273 V</td>
</tr>
<tr>
<td></td>
<td>51.6 kV</td>
<td></td>
<td></td>
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<tr>
<td>$I_{\text{DC PS}}$</td>
<td>585 A</td>
<td>765 A</td>
<td>255 A</td>
</tr>
<tr>
<td>$U_{\text{DC PS}}$</td>
<td>27.7 V</td>
<td>122.4 V</td>
<td>32 V</td>
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<tr>
<td>$I_{\text{AC PS}}$</td>
<td>665 A</td>
<td>540 A</td>
<td>187 A</td>
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<td>$U_{\text{AC PS}}$</td>
<td>990 V</td>
<td>3.22 kV</td>
<td>273 V</td>
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</table>
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DESY II Overview (artist view)
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DESY II with compound inductor (White choke)
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DESY II dipole power supply with Steinmetz circuit
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DESY QP, SP circuit
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![CAS Logo](https://www.cern.ch/)

**ESRF 6 GeV**

<table>
<thead>
<tr>
<th></th>
<th>Dipole</th>
<th>QPF</th>
<th>QPDF</th>
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<td>1500 A</td>
<td>500 A</td>
<td>500 A</td>
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<tr>
<td>$U_{\text{rms Choke/magnet}}$</td>
<td>11 kV</td>
<td>2 kV</td>
<td>2 V</td>
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<td>$I_{\text{DC PS}}$</td>
<td>800 A</td>
<td>200 A</td>
<td>180 A</td>
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<tr>
<td>$U_{\text{DC PS}}$</td>
<td>600 V</td>
<td>200 V</td>
<td>200 V</td>
</tr>
<tr>
<td>$I_{\text{AC PS}}$</td>
<td>800 A</td>
<td>200 A</td>
<td>180 A</td>
</tr>
<tr>
<td>$U_{\text{AC PS}}$</td>
<td>V</td>
<td>V</td>
<td>V</td>
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</tbody>
</table>
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Power supply of ESRF

Rectifier circuit Chopper DC circuit Inverter
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**BE tr ESSY II 1.9 GeV**

<table>
<thead>
<tr>
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<th>Dipole</th>
<th>QPF</th>
<th>QPDF</th>
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<tbody>
<tr>
<td>$I_{\text{max}}$</td>
<td>2277 A</td>
<td>492 A</td>
<td>395 A</td>
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<tr>
<td>$U_{\text{rms Choke/magnet}}$</td>
<td>3112 kV</td>
<td>527 V</td>
<td>423 V</td>
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<td>$I_{\text{DC PS}}$</td>
<td>800 A</td>
<td>200 A</td>
<td>180 A</td>
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<td>$U_{\text{DC PS}}$</td>
<td>120 V</td>
<td>70 V</td>
<td>70 V</td>
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<td>$I_{\text{AC PS}}$</td>
<td>778 A</td>
<td>200 A</td>
<td>200 A</td>
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<tr>
<td>$U_{\text{AC PS}}$</td>
<td>311V</td>
<td>184 V</td>
<td>184 V</td>
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</table>
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Schematic of the BESSY II Power supply
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Power supply at SLS
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Fast ramping machines

- DESY III
- Tevatron
- Fermilab Main Injector
- Cern Antiproton Decelerator
- PETRA

- Ramping times from a second to a minute
- \( U = R \cdot i + L \cdot \frac{di}{dt} \)
  
  Due to the inductance the term demands for a significant higher voltage than for steady state
- Negative voltage has to be applied for down ramping
- Precautions for the mains have to be taken
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**DESY III**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Dipole</td>
<td></td>
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<tr>
<td>$I_{\text{flat top}}$</td>
<td>1160 A</td>
</tr>
<tr>
<td>$U_{\text{flat top}}$</td>
<td>1 kV</td>
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<tr>
<td>$I_{\text{flat bottom}}$</td>
<td>50 A</td>
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<tr>
<td>$U_{\text{flat bottom}}$</td>
<td>42 V</td>
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<tr>
<td>$di/dt$</td>
<td>665 A/s</td>
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<td>Ramping time</td>
<td>4 sec</td>
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DESY III Power supply with dynamic reactive power compensation
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Waveforms of DESY III
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Signals for the DESY III ramp

1st derivation
Reference value
2st derivation
3st derivation
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DESY III Power supply with dynamic reactive power compensation
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Tevatron

<table>
<thead>
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<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$I_{\text{flat top}}$</td>
<td>4400 A</td>
</tr>
<tr>
<td>$U_{\text{flat top}}$</td>
<td>1 kV</td>
</tr>
<tr>
<td>$I_{\text{flat bottom}}$</td>
<td>400 A</td>
</tr>
<tr>
<td>$U_{\text{flat bottom}}$</td>
<td>42 V</td>
</tr>
<tr>
<td>$\frac{di}{dt}$</td>
<td>67 A/s</td>
</tr>
<tr>
<td>Ramping time</td>
<td>60 sec</td>
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</tbody>
</table>
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Tevatron distribution of power supplies

Total of 12 TEV PS's Distributed Around Ring
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Power supply of Tevatron

TEVATRON POWER SUPPLY SYSTEM
POWER CIRCUIT
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Fermilab Main Injector

Main Injector Power Supply Distribution
Bend Bus
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Fermilab main injector data

<table>
<thead>
<tr>
<th>Requirement</th>
<th></th>
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<tbody>
<tr>
<td>Dipole and quadrupole power, peak</td>
<td>120 MVA</td>
</tr>
<tr>
<td>Dipole and quadrupole power, average</td>
<td>60 MVA</td>
</tr>
<tr>
<td>RF, beamline power supplies, peak</td>
<td>30 MVA</td>
</tr>
<tr>
<td>RF, beamline power supplies, average</td>
<td>20 MVA</td>
</tr>
<tr>
<td>Backfeed capability, peak</td>
<td>40 MVA</td>
</tr>
<tr>
<td>Backfeed capability, average</td>
<td>30 MVA</td>
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<tr>
<td>Accelerator cycling time</td>
<td>1.5 sec</td>
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CERN Antiproton Decelerator Cycle
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Antiproton decelerator power supply
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Power supply for the PS-Booster beam transport line with polarity switcher and regenerative circuit
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PETRA-Dipole ring
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Voltage changes due to the ramping of the PETRA-machine
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Slow ramping machines

- HERA
- LEP
- LHC
- Here nearly every lab can be named

- Ramping lasts several minutes or
- Working at steady state
- The variety of power supplies is large and shows in general the state of the art of the power electronics of that time
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HERA Proton Dipole Power Supply

8000 A, +500V, -300V Optical current 5600A
SCR Power supplies

- Power larger than 50 kW
- Currents larger than 800 A
- Voltages higher than 130 V
- Good prices
- Simple design
- Different Solutions according to the specs
  - LC filter
  - Praeg Filter
  - Active filter
SCR supply with LC filter
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SCR Power supply with Praeg filter

400 V
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HERA Buck converter

400 V
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Schematic of the LEP double resonant power supply

125 V, 300 A or 188 V, 200 A or 250 A, 150 V
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LHC 600A/10V, 40V Power supply

Figure 1: \([\pm 600A, \pm 12V]\) Power converter block diagram
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LHC 600A/10V, 40V Power supply
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LHC 600A/10V, 40V Power supply
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SCR unit for LHC transport line with active filter
Pulsed machines

- Linear Collider, sometimes, somewhere
- XFEL, Hamburg
- VUV-FEL, Hamburg

- Machines are working with short pulses between a few µsec up to ms
- Repetition rates between 1 and 50 Hz
- High demands on power supplies
- Suppress the repetition rate toward the grid
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New XFEL power supply for sc QP
+/- 100 A/10V
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XFEL Power supply

(A) $T_1$ off, $T_2$ off, $T_3$ on, $T_4$ on

halfbridge

$u_{out}$

$C_1$

$T_1$

$C_2$

$u_{Tr}$

$T_2$

$C_3$

$iprim$

$UB$

$halfbridge$

$iprim$

$u_{Tr}$

$T_3$

$T_4$

$T_1$ on, $T_2$ off, $T_3$ on, $T_4$ off

isec/2

output filter

$L_1$

$u_{out}$

$Z_L$

(B) $T_1$ on, $T_2$ off, $T_3$ on, $T_4$ off

halfbridge

$u_{out}$

$C_1$

$T_1$

$C_2$

$u_{Tr}$

$T_2$

$C_3$

$iprim$

$UB$

$halfbridge$

$iprim$

$u_{Tr}$

$T_3$

$T_4$

$isec$

$Z_L$

rectifier

output filter

(C) $T_1$ on, $T_2$ off, $T_3$ on, $T_4$ off

halfbridge

$u_{out}$

$C_1$

$T_1$

$C_2$

$u_{Tr}$

$T_2$

$C_3$

$iprim$

$UB$

$halfbridge$

$iprim$

$u_{Tr}$

$T_3$

$T_4$

$isec$

$Z_L$

rectifier

output filter

$u_{out}$

$t_{on}$

$t_{off}$

$t_p$

$t_{delay1}$

$t_{delay2}$

$u_{Tr}$

$Z_L$
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Web Access to the power supply
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Voltage at XFEL Modulator

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Switched mode power supply for constant power

\[ G \]
\[ i_B \] supply current
\[ i_L \] primary current of the transformer
\[ u_C \] voltage of the resonance capacitor
\[ U_{\text{load}} \] output voltage to the switch of the klystron
\[ i_{B1} \] current \( i_B \) at the time \( t_1 \)
\[ L \] primary stray inductivity of the transformer
\[ f \] resonance frequency of the resonant circuit of \( L \) and \( C \)
\[ n \] gear ratio of the transformer and rectifier
\[ T \] period time of the switching frequency of \( S_1 \) and \( S_2 \)
\[ C \] resonance capacitor
\[ U_B \] supply voltage
\[ U_N \] line voltage
\[ C_f \] filter capacitor
\[ L_f \] filter inductance
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Derivation of the equivalent circuit to the switch mode power supply

\[ \frac{C}{2} u_c \]

\[ U_N \]

\[ C_f \]

\[ U_B \]

\[ S1 \]

\[ S2 \]

\[ T_r \]

\[ D1 \]

\[ D2 \]

\[ \approx \]

\[ G \]

\[ C_{\text{load}} \]

\[ U_{\text{load}} \]

\[ t_1 \]

\[ t_2 \]

\[ T/2 \]

\[ t \]

\[ u_c \]

\[ u \]

\[ i_L \]

\[ i_B \]

\[ I_B \]

\[ Zerannten \]

\[ \text{switching} \]
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Series connection of buck converters
Conclusion

• There are a lot of very interesting power supplies in the machines
• This was only a very short overview of what is installed into machines over the world
• It shall give an idea what kind and where solutions and help are to find when someone encounters a new problem
• A very good source of information is:
  • Joint Accelerator Conferences Website
  • http://accelconf.web.cern.ch/AccelConf/
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Thanks for your attention