

Design and Preliminary Results of the COMPASS Power Supplies Filters

J. Havlicek^{1,2} and J. Zajac¹

¹ Institute of Plasma Physics AS CR, v.v.i., Association EURATOM/IPP.CR,
Za Slovankou 1782/3, 182 00, Prague 8, Czech Republic.

² Charles University in Prague, Faculty of Mathematics and Physics, Prague, Czech Republic.

Abstract. The COMPASS tokamak uses rectifying thyristor converters as Power Supplies for the major slow coils circuits. 24-pulse thyristor converter is used for Toroidal Field circuit and 12-pulse converters are used for Magnetizing, Equilibrium and Shaping Field circuits. A noise generated by the switching of the converters negatively influences diagnostics measuring the plasma. The article describes design phase and some preliminary results of the filters for the Power Supplies.

Introduction

The COMPASS tokamak [Pánek *et al.*, 2006] currently uses six circuits [Havlicek and Hronová, 2008; Havlicek and Horacek, 2008] of the magnetic field coils to control the plasma current, shape and position. The coils are organized into the circuits using two dedicated linkboards which allow to change plasma shape by selecting different coils. There are three types of Power Supplies (PS) used to supply different circuits:

- 1) 24-pulse thyristor converter: (1440–2040 Hz)
 - TFPS ($0 \div 92$ kA) — Toroidal Field Power Supply for creation of up to 2.1 T field.
- 2) 12-pulse thyristor converters: (720–1020 Hz)
 - MFPS ($-18 \div 16$ kA) — Magnetizing Field Power Supply for plasma current drive and ohmic heating.
 - EFPS ($0 \div 16$ kA) — Equilibrium Field PS for generating vertical magnetic field which prevents plasma column from expanding its main radius.
 - SFPS ($0 \div 12$ kA) — Shaping Field PS for shaping and creating divertor plasma configuration.
- 3) Fast Amplifiers based on MOSFET transistor H-bridge: (40 kHz)
 - BR (± 5 kA) — horizontal magnetic field for fast feedback control [Janky *et al.*, 2011] of the vertical plasma position.
 - BV (± 5 kA) — vertical magnetic field for horizontal plasma position feedback.

All of these Power Supplies are in principle switched-mode power supplies with sharp changes in the voltage applied to the tokamak coils. The tokamak coils are mostly inductive loads with self-inductances in range of 100–3000 μ H and resistances in range of 2–50 m Ω (see Table 2 in Realization and status section). Due to the inductance the current ripple generated by repetitive voltage changes of the switched-mode power supplies is generally low (less than 1 % for thyristor converters for typical current values). Nevertheless this current ripple still poses a problem because it generates a significant noise in many diagnostics [Weinzettl *et al.*, 2011].

There are two major reasons for the noise in diagnostic measurements. First is the grounding of many diagnostics - those grounded to the tokamak vacuum vessel where a current is flowing. This current is generated inductively by the tokamak coils and reaches up to 40 kA during plasma current breakdown and then ≈ 3 kA ripple with frequency of the 12-pulse converters during the plasma flat-top phase. Second source of the noise is direct inductive coupling between tokamak coils and various diagnostics — this can be coupling to the electronic circuits, coupling to the data cables (usually twisted shielded pairs or coaxial) or coupling to diagnostic coils in case of magnetic diagnostics.

The COMPASS tokamak uses two flywheel generators to provide energy for the Power Supplies [Zajac *et al.*, 2009]. The maximal rotation speed of the flywheels is 1700 rpm and the flywheels can slow down to 1200 rpm. Corresponding frequency of the 24-pulse thyristor converter is changing during the discharge from 2040 Hz ($24 \times 3 \times 1700$ rpm / 60 s) to 1440 Hz (or 1020 Hz to 720 Hz for 12-pulse converters feeding poloidal field coils). It should be noted that the flywheels can start the discharge from lower than maximal rotation speed and 1400 rpm is commonly used.

Two Fast Amplifiers [Havlicek *et al.*, 2013] are H-bridges based on MOSFET transistors with Controller Unit which uses fixed frequency (40.138 kHz) to apply positive or negative voltage to the load based on the requested and internally measured current.

This article describes design and some preliminary measurements of filters for all four thyristor converter Power Supplies. Filters for two Fast Amplifiers are not yet designed.

Filter principle

The principle of the filters will be explained on EFPS circuit using measurements of the temporary testing filter unit manufactured for validation of the concept. The basic idea is to use a standard LC filter, however capacitor of such filter creates an oscillating LC circuit together with tokamak coils. These oscillations must be suppressed by damping resistor in parallel with the capacitor.

Two 6-pulse thyristor converters are supplied from three phase transformer (not depicted in Fig. 1) with two secondary windings — one in triangle, one in star configuration — providing six phase shifted voltage sine waves. The two 6-pulse converters are connected in parallel through two choke coils (each $45 \mu\text{H}$, effectively $L_0 = 22.5 \mu\text{H}$) to tokamak EF circuit and decoupling transformer EF-BV (temporary variant with high resistance $10 \text{ m}\Omega$) which together forms $R_{\text{tok}} = 26.5 \text{ m}\Omega$ and $L_{\text{tok}} = 1450 \mu\text{H}$.

The filter consists of capacitor C_f , series resistor R_s and parallel damping resistor R_p . The higher frequencies of the voltage generated by converter create a current which can pass through choke coils L_0 and L_{added} and capacitor C_f (Fig. 1a, red) while lower frequencies current is applied to the tokamak coils. Part of the converter current also goes into through $L_0 + L_{\text{added}}$ and damping resistor R_p (Fig 1b, red) effectively lowering the current available for the tokamak coils. The effective voltage applied to the tokamak coils U_{tok} consists of converter voltage U_{conv} (switched, sharp changes) and voltage generated in choke coils L_0 and L_{added} by passing current:

$$U_{\text{choke}} = (L_0 + L_{\text{added}}) \frac{d(I_{\text{filter}} + I_{\text{tok}})}{dt}.$$

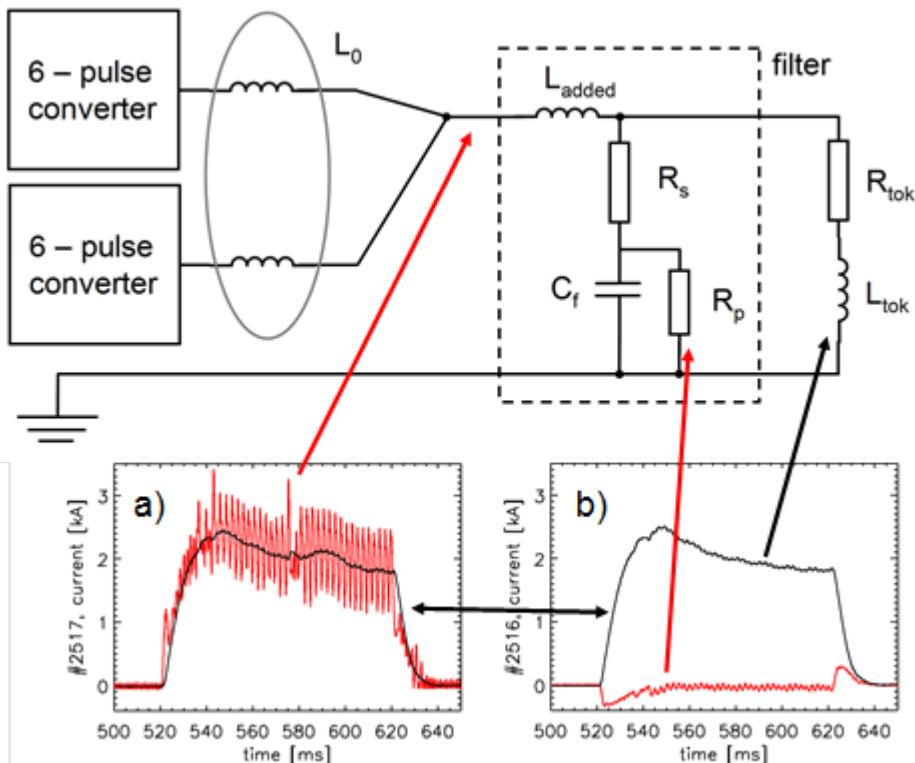


Figure 1. Filter principle for 12-pulse converter, a) 720–1020 Hz current ripple (red line) passes through choke coils L_0 and L_{added} to capacitor C_f which filters the current to tokamak coil (black line), b) current in the damping resistor R_p (red line). Both cases for $L_{\text{added}} = 0$, $C_f = 4.2 \text{ mF}$, $R_s = 75 \text{ m}\Omega$ and $R_p = 1 \Omega$ used in temporary testing filter.

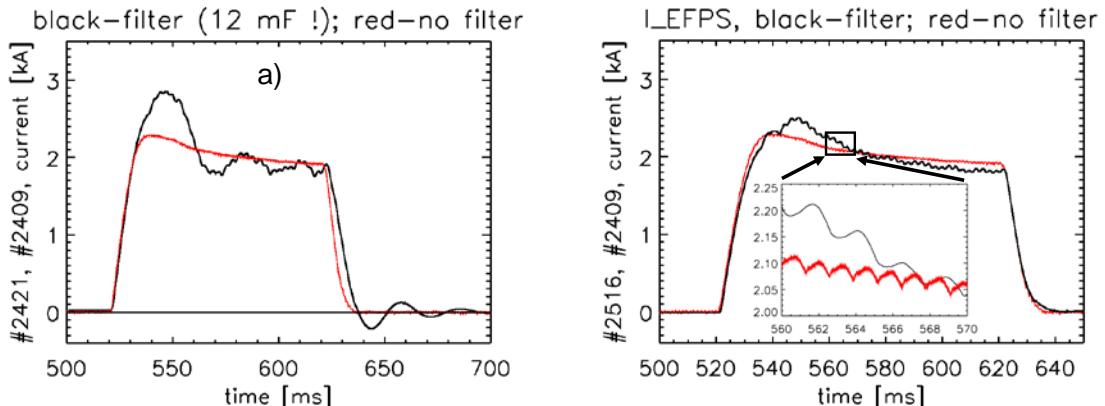


Figure 2. a) I_{tok} with higher capacity (12 mF !) and no damping resistor leads to ≈ 26 ms oscillations, b) test without L_{added} , $C_f = 4.2$ mF, $R_p = 1$ Ohm, $R_s = 75$ mOhm leads to smoother current in tokamak coil when compared with unfiltered.

Considering the fact that high frequency part of the current passes through filter, the resulting U_{tok} is smoothed in comparison to U_{conv} .

The black line in Fig. 1a, b and red line in Fig. 2 shows various realizations for requested tokamak current (2kA, 100 ms long rectangular pulse) during tests of temporary filter unit.

Figure 2a shows an experiment with higher capacity and disconnected damping resistor R_p . The black line shows oscillations of the tokamak current in comparison with unfiltered tokamak current (red). The oscillations have period $T = 2\pi\sqrt{L_{\text{tok}}C_f} = 26$ ms. This experiment clearly demonstrates the necessity of the damping resistor R_p even though the resistor lowers power available for tokamak coils.

Figure 2b shows direct comparison between unfiltered tokamak current and current filtered by testing filter unit. It should be noted that smooth oscillations on the filtered current are exaggerated by the incorrect regulation. During these tests the control of the current was incorrect because the EFPS converter controller discretely measured current in the converter and did not take into account current flowing into the filter. The filter current is measured in the final realization and provided to the controller to have correct regulation of the current going into tokamak coils.

Performed simulations

The actual filters for the TFPS, MFPS, EFPS and SFPS Power Supplies were designed after extensive simulations to achieve optimal performance with given constraints. The desired parameters of the filters were: 1) minimal achievable distortion of the circuit current response to the rectangular requested current pulse and 2) maximal suppression of the current ripple (1 kHz or 2 kHz). The constraints were:

- use of available capacitors MKK B25650 with capacity 4.2 mF, $U_{\text{max}} = 2.5$ kV, $I_{\text{steady,max}} = 410$ A
- financial limit to the overall cost — mostly limits possibility to add choke coils L_{added}
- spatial limit in the assembly area
- manageable power load of the damping resistor R_p , which limits its lowest value for given PS maximal voltage

The simulations will be described on the EFPS filter example. The 5Spice Analysis Software [Andresen] was used for initial filter design and then the results were confirmed by the Power Supplies manufacturer in the more realistic Matlab Simulink model with full description of the converter including control loop.

Figure 3 shows schematics (a) of the EFPS circuit with the filter. The schematics contains simplistic approximation of the converter in the form of DC voltage with 1kHz triangular voltage superimposed, coils L_0 and L_{added} , filter with added parasitic inductances L_p and L_s to test sensitivity to such parameters, and tokamak coils L_{tok} with R_{tok} .

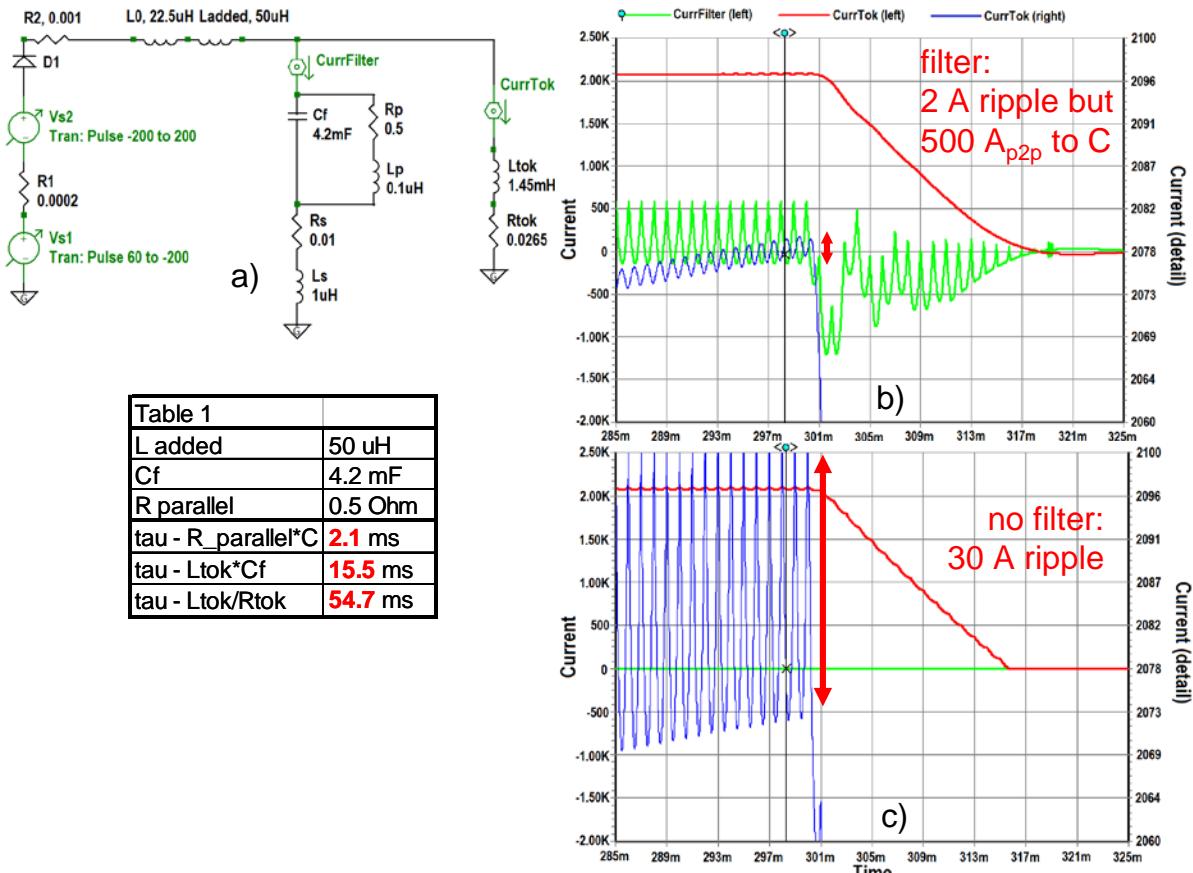


Figure 3. 5Spice Analysis Software used to simulate all circuits, here EFPS circuit is shown.

a) Schematics, b) EF current with filter, c) without filter.

Table 1 summarizes the values of the selected electrical parts in the filter and time constants of the different parts of the entire circuit. The reaction speed of the EFPS circuit is determined by the tokamak coils inductance and resistance (RL circuit, time constant 54.7 ms) and by available voltage of the converter (270 V). The speed can not be significantly influenced by the filter design because tokamak coils have inductance much larger than L_0 and L_{added} . The filter capacitor creates oscillating LC circuit with tokamak coils (time constant 15.5 ms). These oscillations would negatively influence plasma control and must be damped. This is achieved by using damping resistor R_p which creates RC circuit with capacitor C_f . The time constant of the RC circuit $R_p \times C_f$ (selected 2.1 ms) must be much smaller than time constant of LC circuit. This is one constraint in the filter design.

The another constraint in the filter design is power dissipated in the R_p resistor. EFPS filter uses 0.5 Ω which can be loaded with effective 150 kW when EFPS converter provides its maximal effective voltage 270 V.

Choke coil L_{added} increases inductance of the already used choke coils (two 45 μ H parallel = 22.5 μ H). The higher value of L_{added} results in better filtration and the value is limited mostly by financial consideration. The reaction speed of the entire circuit (54.7 ms) is not significantly lowered as long as the tokamak coils have much larger self-inductance than choke coils.

Figures 3b and 3c show circuit response to the current request jump from 2 kA to 0 A (red line, left axis and its detail: blue, right axis) together with current to the filter (green line, left axis). It is visible that the current ripple without filter is ≈ 30 A_{p2p} while decrease of the current from 2 kA to 0 A is 15 ms long. The filter decreases the current ripple significantly and response to the current jump is reasonably undisturbed.

The final design of the EFPS filter uses $C_f = 4.2$ mF consisting of 2×2 capacitors MKK B25650 (each 60 kg, 4.2 mF, 2.5 kV, 410 A), resistance $R_p = 0.5$ Ω (rated for 300 kW/1 sec then 10 minutes pause, 31 kg) and $L_{\text{added}} = 50$ μ H (choke coil TLV 56/29, 20 kA/1 sec then 10 minutes pause, 155 kg, 1000 V).

Preliminary measurements

Preliminary measurements of the filters influence on the diagnostics measurements are presented in this chapter. Loop voltage measured by flux loop (toroidally wound wire) is the best to show the filter influence as it is directly proportional to the derivative of any toroidal current — either current in the MF, EF, SF, BR and BV circuit coils (which are all Poloidal Field coils — PF coils) or the toroidal component of the poloidal current flowing around the vacuum vessel ports. The poloidal current can be generated by changes of TF coils current.

Figure 4 shows a loop voltage measured by Flux loop # 4 located on the High Field Side ($R = 0.325$ m, $Z = 0$ m). There are three cases depicted:

1. “only TF filtered” — MF, EF and SF circuits are running and are not filtered while TF coils are filtered. Voltage structures with 840 Hz frequency (1400 rpm, 12-pulse) are visible while 1680 Hz voltage peaks from TF switching are suppressed.
2. “no filter” — all circuits are running without filter, both types of voltage structures and peaks are present.
3. “TF remains” — TF coils are unfiltered while all PF circuits with exception of EFPS are disconnected. EFPS is filtered by temporary testing filter unit. 1680 Hz voltage peaks are visible while 840 Hz voltage structures are suppressed.

These preliminary measurements show promising improvement in the noise observed by loop voltage. It should be stated that not only magnetic signals are influenced by the Power Supplies current ripple. The probe measurements are particularly sensitive to this type of noise (but mostly from Fast Amplifiers which are not filtered yet) and some of the bolometry channels are also affected.

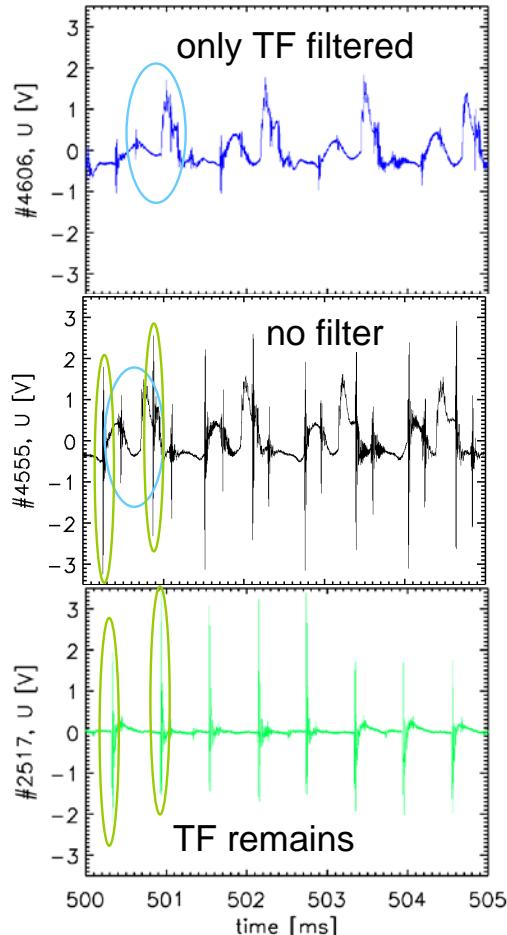


Figure 4. Loop voltage measured by the Flux loop 4 on the HFS (High Field Side, near central solenoid), all circuits currents are zero during the measurement (worst case scenario — highest noise). 840 Hz and 1680 Hz structures marked by ellipses.

Table 2				
Power Supply	TF	EFPS	SFPS	MFPS
L_0 [uH]	5.5	22.5	35	50
L_{tok} [uH]	2500	1450	760	3000
R_{tok} [mOhm]	2.7	26.5	40.7	37
L_{added} [uH]	10.5	50	100	50
C_f [mF]	6.3	4.2	2.8	2.8
configuration of C_f	2x3	2x2	3x2	3x2
R_p [Ohm]	1	0.5	0.8	1
R_s [mOhm]	10	10	10	10
$\tau R_p * C_f$ [ms]	6.3	2.1	2.24	2.8
$\tau L_{tok} * C_f$ [ms]	24.9	15.5	9.2	18.2
$\tau L_{tok}/R_{tok}$ [ms]	925.9	54.7	18.7	81.1

Realization and status

The filters were designed (see Table 2), manufactured and installed. All individual filters were tested together with their respective Power Supply with exception of MFPS filter (due to the time constraints in COMPASS operation and availability of experts from Power Supplies manufacturer). A cross-talk problem between individual PF circuits was discovered — current in the MFPS circuit generates current going through EF coils and EFPS filter. This problem remains to be solved, probably by adjusted control of Power Supplies. Only TFPS filter is being used now.

Conclusion

Design of the filters for the Power Supplies based on the LC filter with strong resistive damping was described. Preliminary results show promising reduction of the observed noise. The filters were manufactured and installed and will be used in near future.

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References

- Andresen, R.P., 5Spice Analysis Software, <http://www.5spice.com>
- Havlicek, J. and O. Hronová, Characterization of Magnetic Fields in the COMPASS Tokamak, *WDS'08 Proceedings of Contributed Papers: Part II — Physics of Plasmas and Ionized Media*, pp. 110–114, 2008.
- Havlicek, J. and J. Horacek, Modelling of COMPASS tokamak PF coils magnetic fields, 35th EPS Conference on Plasma Physics, Hersonissos, June 9 – June 13, 2008 ECA Vol.32D, P4.080, 2008.
- Havlicek, J., R. Hauptmann, O. Peroutka, M. Tadros, M. Hron, F. Janky, P. Vondracek, P. Cahyna, O. Mikulin, D. Šesták, P. Junek, R. Pánek, Power supplies for plasma column control in the COMPASS tokamak, *Fusion Eng. Des.*, 2013, in print.
- Janky, F., J. Havlicek, D. Valcárce, M. Hron, J. Horacek, O. Kudlacek, R. Panek and B.B. Carvalho, Determination of the plasma position for its real-time control in the COMPASS tokamak, *Fusion Eng. Des.* 86 [6–8], 1120–1124, doi:10.1016/j.fusengdes.2011.01.143, 2011.
- Pánek, R., O. Bilyková, V. Fuchs, M. Hron, P. Chráska, P. Pavlo, J. Stöckel, J. Urban, V. Weinzettl, J. Zajac and F. Žáček, Reinstallation of the COMPASS-D Tokamak in IPP ASCR, *Czechoslovak Journal of Physics*, 56(2), B125–B137, 2006.
- Weinzettl, V., et al., Overview of the COMPASS diagnostics, *Fusion Eng. Des.* 86 [6–8], 1227–1231, 2011.
- Zajac, J., R. Pánek, F. Žáček, J. Vlček, M. Hron, A. Křivská, R. Hauptmann, M. Daněk, J. Šimek, J. Prošek, Power supply system for COMPASS tokamak re-installed at the IPP, Prague, *Fusion Eng. Des.* 84 [7–11], 2020–2024, 2009.