ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

Fakulta elektrotechnická

Katedra elektrických pohonů a trakce (K 13114)

(Czech Technical University in Prague, Faculty of Electrical Engineering)
(Department of Electric Drives and Traction)

Studie napájecích zdrojů pro tokamak COMPASS-U

(Study of Power Supplies
for
COMPASS-U Tokamak)

Vypracoval (Created by): prof. Ing. Jiří Lettl, CSc.

Datum (Date): květen 2016 (May 2016)

Identifikace zpracovatele (identification of contractor):
ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
Fakulta elektrotechnická
Katedra elektrických pohonů a trakce (13114)
Praha 6, Technická 2
prof. Ing. Jiří Lettl, CSc.
+420 22435 2147
lettl@fel.cvut.cz

Content

1. Introduction

This study is conducted on the base of Institute of Plasma Physics of the Czech Academy of Sciences instructions and requests.
The goal is to explore the possible solutions for the Power Supply system for the planned new COMPASS-U tokamak. The subject of the study is the solution for the Power Supply system from the high-voltage supply line up to the delivery of power to individual coils and devices at the planned COMPASS-U tokamak.

The main goals of the study are:

- Acquisition of information about different options of and possibilities for the Power Supply system solution, its individual components, mainly generators, transformers and converters, respectively.
- Acquisition of price estimates for individual options of the solution, i.e. for the individual main components of the Power Supply system.
- Choice of an appropriate reference solution including its indicative pricing which will be integrated into the Feasibility study of the whole new COMPASS-U tokamak which will subsequently serve as supporting material for a grant application to the Operation Programme Research, Development and Education.

The aim is to find a solution with maximal utilization of already installed Power Supply system devices of the existing COMPASS tokamak. Nevertheless, major changes in the current solution are to be expected, because of the much higher planned parameters of the new COMPASS-U tokamak, already in the beginning of the study. Planned parameters of the new COMPASS-U tokamak:

- The major radius of the tokamak will increase from 56 cm to 84 cm.
- Induction of the main toroidal field will increase from 2.1 T to 5T.
- Maximal plasma current will increase from 350 kA to 2000 kA.
- Maximal plasma discharge duration will increase from 500 ms to 3000 ms.

The client (IPP) in the scope of the COMPASS-U project expects the following changes in the Power Supply system:

- Enhancement of the current flywheel generators with the goal of increasing the usable energy.
- Construction of an additional generator / generators.

- Reconstruction of the existing transformers, respectively delivery of new ones and associated changes in the high- and low-voltage switching stations.
- Extension of the quantity and current rating of thyristor converters, alternatively addition of new ones or replacement by IGBT-based converters.
- Enhancement of safety and control capacities.
- Solution of the excess energy dissipation/recuperation that returns from the tokamak coils at the end of the discharge.

2. Current Status of the Power Supply System

The Power Supply system currently installed in the IPP building for the COMPASS tokamak is briefly described in this chapter, because its maximal utilization is requested.

The basic constraint is the electricity supply power capacity from the electric power distribution system. The existing Power Supply system is adjusted to work with a reserved power of 1 MW. Reserved power of 2 MW has been provisionally arranged with the power distributor for the COMPASS-U tokamak, higher power supply capacity is not possible. However, the Power Supply system requires several orders of magnitude higher power, even though only for a very short period of time. For these reasons two flywheel generators are installed to meet the energy demands of the COMPASS tokamak. Each of the flywheel generators provides up to 35 MW (50 MVA) power and usable energy 46 MJ. The nominal operational range of the rotation speeds is between 1700 rpm and 1300 rpm.

The system is designed in such a way that one of the generators satisfies the demands of the main toroidal magnetic field (further only TF – Toroidal Field) circuit and the other one satisfies the demands of all the poloidal magnetic field (further only PF – Poloidal Field) circuits and auxiliary heating systems. The flywheel generators provide energy for two independent 6 kV three phase high voltage grids. If only one generator is operational the grids are connected.

Individual tokamak coil converter circuits have separate transformers with specific voltages. There are two transformers available for the TF circuit (24 MVA each), two transformers for the flywheel generator exciters (1.3 MVA) and six different transformers (from 0.75 MVA to 18 MVA) for PF circuits and auxiliary heating systems (the transformers are labelled MFPS, EFPS, SFPS, FFPS, Kly, NBI).

The COMPASS tokamak was designed in such a way that each PF circuit controls an independent physical plasma parameter (radial position, vertical position, plasma current, plasma shape). This design enables plasma control to be simple and decreases the number of independent converters. The disadvantage is the decreased flexibility of plasma shaping. Modern tokamaks use a system where each PF coil has its own independent Power Supply. COMPASS-U will use the same modern design with separate Power Supplies for each of individual coils. Therefore, there will be a lot more converters at the COMPASS-U tokamak.

The COMPASS tokamak currently uses five different types of converters:

- 24-pulse thyristor converter – Toroidal Field Power Supply (0 ÷ 91 kA, 500 V).

- 12-pulse thyristor converters – three Power Supplies with -18 ÷ 16 kA and voltages up to 800 V for Magnetizing (MFPS), Equilibrium (EFPS) and Shaping (SFPS) circuits.
- Fast Amplifiers (FA) based on MOSFET transistor, H-bridge with switching frequency 40 kHz and +/- 5 kA current.
- Vertical Kicks Power Supply (VKPS) based on IGBT transistors with intermittent frequency up to 4 kHz, +/- 5 kA current and operational voltage 1.2 kV.
- RMP (Resonant Magnetic Perturbations) Power Supplies based on MOSFET transistor, H-bridge with switching frequency 40 kHz and +/- 4 kA current. The design is similar to the Fast Amplifiers, but the used transistors enable a higher operational voltage (up to 190 V).

The thyristor converters were manufactured by the supplier of the original COMPASS tokamak Power Supply system. The MOSFET and IGBT Power Supplies were designed and manufactured in-house at IPP later.

3. Energy Requirements for the COMPASS-U Tokamak

The COMPASS-U tokamak with its 5 T toroidal magnetic field and 2000 kA in plasma current will have significantly higher energy requirements than the existing COMPASS tokamak. The ohmic losses will be limited by cooling TF (Toroidal Field) and PF (Poloidal Field) coils to the temperature of liquid nitrogen, effectively lowering the resistivity of the copper coils approximately five times.

From the point of view of power demands, the fundamental systems are:

- Toroidal Field coils
- Poloidal Field coils
- So called additional heating systems

Toroidal Field Coils

Figure 1 shows the COMPASS-U TF coils reference design provided by IPP.

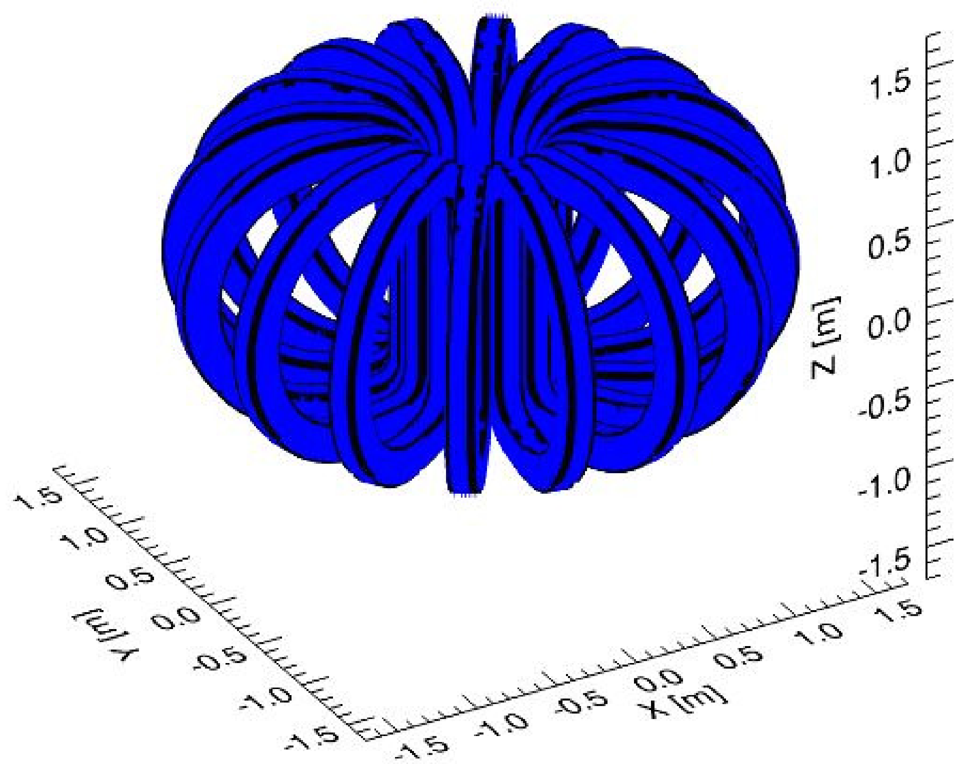


Figure 1 – COMPASS-U tokamak TF coils reference design

Calculations performed by IPP show that, with one currently existing generator (not-upgraded), the Toroidal Field of the COMPASS-U tokamak would achieve either (a) 2 tesla for 0.8 seconds with TF coils at a room temperature or (b) 3 tesla for 1 s duration with TF coils cooled to liquid nitrogen temperature. These values can be achieved without any upgrades of the currently existing flywheel generators, transformers or thyristor converters. The safety margins of the Power Supply System would be smaller, but acceptable. Nevertheless, the required 5 T could not be achieved with this approach alone. A significant increase of available energy is required to increase the toroidal magnetic field to 5 tesla.

The IPP personnel performed a simulation of current, voltage, power, and energy waveforms necessary to reach 5 T in the reference TF coils, shown in Figure 2.

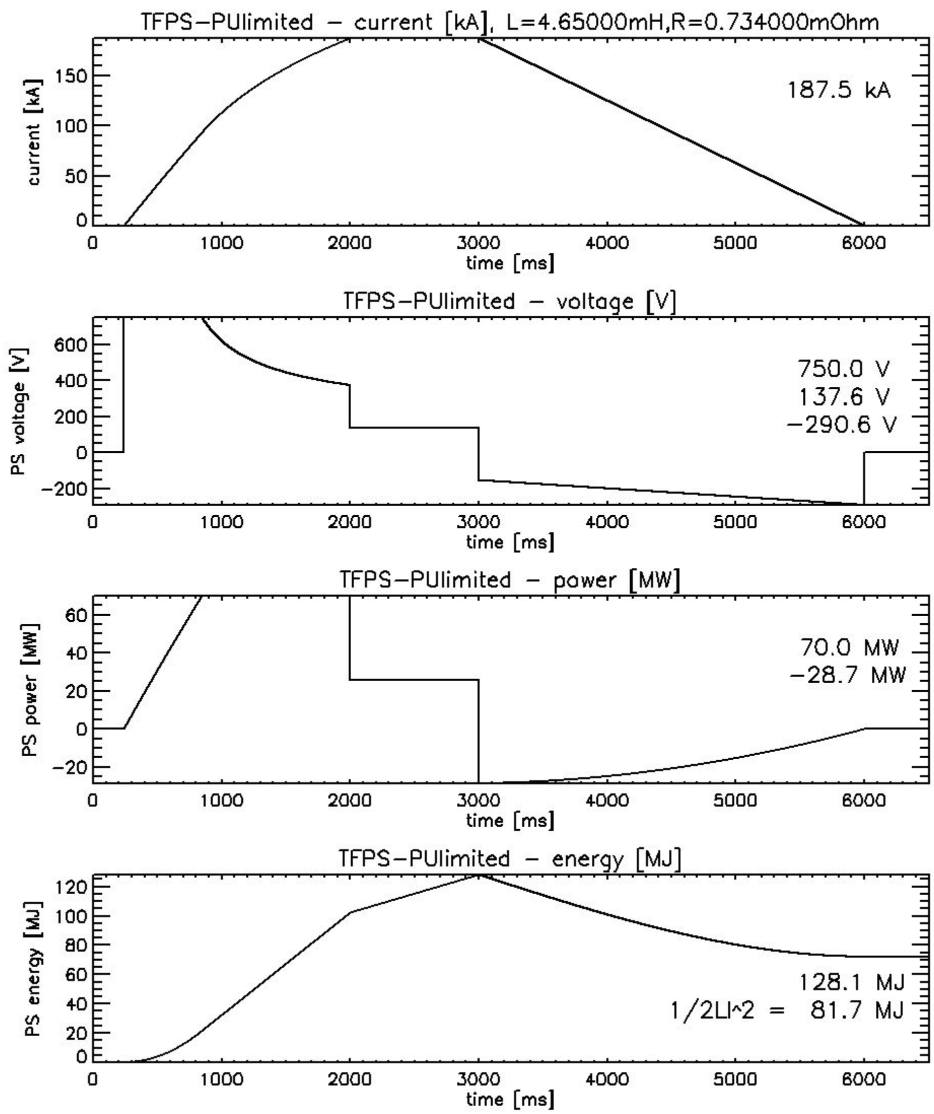


Figure 2 – Simulation of current, voltage, power and energy waveforms necessary to reach 5 T

The simulation was performed for reference design with 16 TF coils and with 7 turns in each of them. It is not a goal of this study to evaluate the selected reference design, only to use the particular TF coils reference design for the purpose of the Power supply system calculations.

The key point is that the number of turns can be changed, while simultaneously keeping the mass constant. This change would result in the identical power, energy and ohmic losses, while changing current and voltage. For example, the increase of the number of turns two times (14 in one coil) would result into 4x higher self-inductance of the circuit, but then two times lower current can be used to reach the identical magnetic field. The two times lower current can be achieved with two times higher voltage in the identical time point as in the reference case. The number of turns in one coil can be changed in range which is determined by manufacturability, mechanical strength and longevity of the TF coil. Nevertheless, the fundamental point for the purpose of this study in the area of the Power Supply system energy sources (generators) is the determination of the required power and energy, which was performed.

The performed reference simulation assumes that the TF coils are powered from two existing generators with total power of 70 MW (2x35 MW), but upgraded to higher available energy content. The energy in the magnetic field is 81.7 MJ, the ohmic losses are 46.4 MJ (until the time t = 3000 ms).

The total maximal energy in the magnetic field, in the ohmic losses of the TF coils and of the inlet cables is 130 MJ (while neglecting losses in the converters, transformers and generators).

The simulation also assumes that the electrical energy is recuperated from the magnetic field into the generators during the current ramp-down.

Poloidal Field Coils

The COMPASS-U tokamak will have all Poloidal Field coils supplied by independent converter, which is a modern concept used by tokamaks. Figure 3 shows distribution and names of individual PF coils of the COMPASS-U tokamak.

Generally, it is possible to assume that the total energy of all PF coils and plasma in the poloidal magnetic field will be < 40 MJ, but the ohmic losses in the PF coils will be significantly higher (the cross-section of the turns is significantly lower than in the TF coils).

The expected time evolution of the plasma current waveform during the experiments with maximal parameters is:

- current ramp-up to 2000 kA with duration of 700 ms

- then 1000 ms of current flat-top
- and current ramp-down back to the zero with duration of 700 ms

The time evolution of the current in the coil CS1U, described in Figure 4 by values (-2.17+/-4) MAt, is a superposition of (a) -2.17 MAt with the identical waveform as the plasma current, and (b) of current swing from +4 MAt to -4 MAt which is performed during the plasma existence duration (i.e. 2.4 seconds). The term (a) shapes the plasma and, therefore, must be proportional to the plasma current, while the term (b) creates the change of the magnetic field flux and, therefore, the voltage maintaining the plasma current in the tokamak.

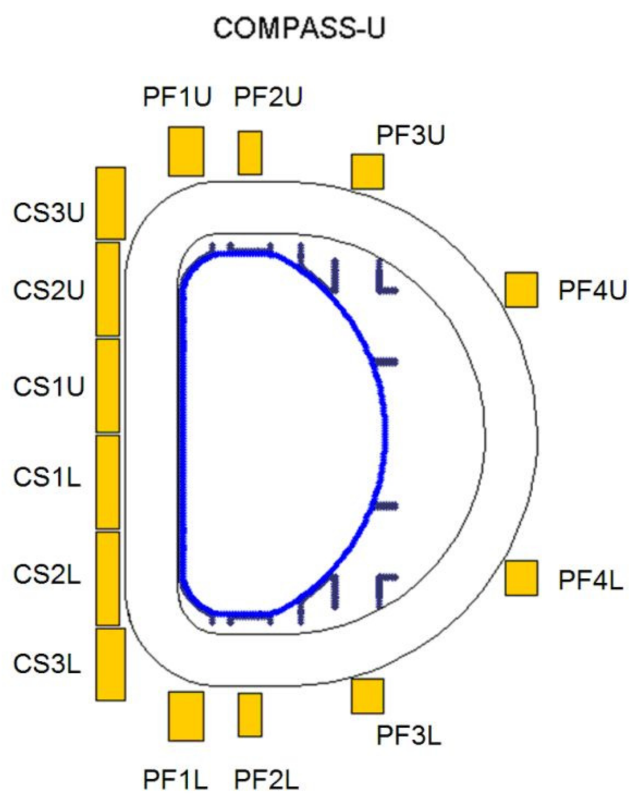


Figure 3 – Names and distribution of the Poloidal Field coils (yellow colour). The blue colour shows contours of the vessel, black colour shows the contour of the TF coils.

The currents in the individual PF coils are shown in Figure 4 (the currents are stated in MAt – mega-ampere-turns).

The additional exact information about currents, voltages, powers and consumed energy in the individual PF coils were provided by IPP during processing of the study.

Additional Heating Systems

The following additional heating systems were assumed for the tokamak in the study assignment:

- 2 x 0.5 MW of heating provided by Neutral Beam Injection using the existing but upgraded NBI injectors
- (3-4) x 1 MW of heating provided by newly built Neutral Beam Injectors
- 4 x 0.5 MW of heating provided by Electron Cyclotron Resonance Heating (ECRH)

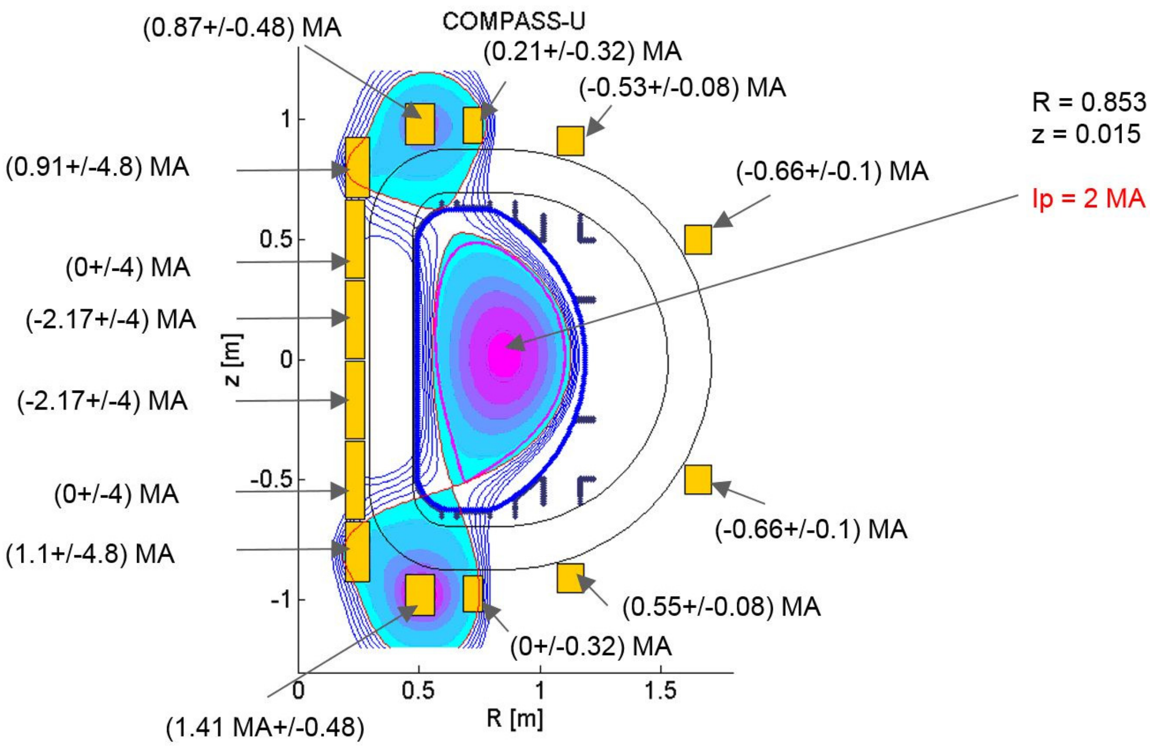


Figure 4 – Currents in the individual PF coils.

The additional heating systems will have together the power injected into the plasma 7 MW. The efficiency of the heating systems is 30-40 %, therefore, the input power is approximately 23 MW. The duration of the heating is expected to be 1-2 seconds, therefore, the energy consumption is approximately 46 MJ.

Considering the effort to assure the upgradeability of the COMPASS-U tokamak in following decades, the values 23 MW and 46 MJ for additional heating systems should be considered to be minimal. The Power

Supply system should be designed with possibility of upgrade for the case when the power and energy requirements of the additional heating systems are increased two to three times.

Main Input Parameters

Input parameters of the solution:

	Current status		Target parameters	
winding	**I1 [kA]**	**t1 [s]**	**I2 [kA]**	**t2 [s]**
TF	92	0,5	180	3 s
EFPS	18	0,5	X	3 s
SFPS	12	0,5	X	3 s
MFPS	12	0,5	X	3 s

Table legend:

I1 - present current amplitude, I2 target value of the current

t1, t2 – duration of the pulse for the present and target situation

Power requirements for the Power Supplies in the original and planned arrangement

winding	P1 [MW]	P2[MW]	L*di/dt [V]
TF	32,2	x	140,40
EFPS	5,4	x	800,00
SFPS	4,8	x	600,00
MFPS	7,8	x	209,40
Total:	50,2		

Table legend:

P1, P2 – required maximal power of the original (P1) and planned (P2) arrangement

L*di/dt – voltage required for the initial ramp-up current slope

4. Energy source - Generators

The study is based on the current status of the Power Supply system of the COMPASS tokamak and it assumes maximal utilization of existing generators. An extension of power and current rating of existing Power Supplies with additional units up to 340 MJ of usable energy is assumed. This follows from the power demands for the new tokamak.
It is obvious that the power and usable energy from the existing generators is insufficient for the power supply of the COMPASS-U tokamak. Therefore, it is clear that it will be necessary to install additional generators. Unfortunately, they take up a considerable share of the whole investment, therefore a solution was sought which would maximally utilize (in the terms of the Power Supply system energy) existing generators and thereby reduce the demands on the new generators and thus also the size of the investment.

Originally, the initial options being considered were new generators in three versions:

- Minimal option: Two generators with an output power of 2 x 35 MW, so of a practically identical construction as the existing generators, but with a significantly larger flywheel, and therefore a usable energy of at least 2 x 100 MJ.
- Medium option: Two generators with an output power of 2 x 50 MW, so of a similar construction as the existing generators, but with a significantly larger flywheel, and therefore a usable energy of at least 2 x 100 MJ.
- Large option: Two generators with an output power of 2 x 75 MW with a usable energy of 2 x 225 MJ.

The minimal option would be advantageous in terms of the price (it is the cheapest one of the options being considered), but a disadvantage is the relatively low output power which has negative impact on the current ramp-up. Furthermore, the option is limited from the point of view of tokamak upgradeability.
The medium option has an advantage in comparison with the minimal option in the higher output power and thus a possibility of faster current ramp-up.
The large option covers even the replacement of the existing generators, including a power reserve for potential expansion of the tokamak. This option is mostly a matter of price.

The options stated here were considered by the client (IPP). The specific power and energy demands and their distribution for individual circuits emerged from the initial requirements for the tokamak. These were subsequently discussed with the client and based on these discussions the requirements for the generators were specified.

It is worth mentioning that the above stated output power ratings come from label powers on the existing generators. This rating is something as a power equivalent which does not correspond to (even a hypothetical) constant load of the generators which are not dimensioned for constant load. The necessary peak output power delivered during the duration of the pulse (3 seconds) is crucial for discussions with potential generator suppliers, respectively for the contract instructions.

In this study the generators are not described in detailed terms, because only the output power and usable energy from the generators are crucial for the purpose of the Power Supply system and the duration of increase of the rotation speed to the initial operation rotation speed is important from the operational point of view.

Below in the part on economical evaluation of individual options the term "generator" refers to the whole unit of the flywheel generator including accessories, i.e. the start-up engine, generator, flywheel, generator exciter, oil management, ventilation, cooling, etc.

Utilization of the Existing Generators

As stated previously, the goal is the maximal utilization of existing generators in order to decrease the demands on the new generators. Therefore, the study dealt with the possibility to increase of the usable energy from existing flywheel generators. The output power from the generators is given by their construction and thus it cannot be increased. Presently, the generators can deliver 2x46 MJ of usable energy at rotation speeds in the range from 1700 rpm to 1300 rpm.

The usable energy can be theoretically increased using two approaches:

- change of the flywheel
- change of the rotation speed range

The replacement of the mass flywheels would have the goal of increasing the moment of inertia of the whole rotating mechanical system and thereby an increase of the accumulated kinetic energy. However, this option is not technically feasible. The flywheels are hot-pressed onto the shaft, and therefore cannot be replaced without damaging the shaft. Furthermore, there would be issues with the installation location, because the new flywheels would be longer than the current ones and would not fit into the existing space. The enlargement of the flywheel through expanding its diameter is not possible because of the speed on the periphery which already reaches 170 m/s. The bearings would likely also be overloaded, same as the clutch, but this was not investigated in detail, because this option did not seem technically feasible form the beginning.

The solution would be to expand the range of operational rotation speeds in both the top (initial) and bottom (final) limits. These are presently 1700/1300 rpm.

First the increase of the initial rotation speed was addressed, because it would be the easiest way to reach higher energy. However, utilization of rotational sources in boundary regimes (top rotation speeds) gives rise to the risk of damaging the clutch and also slipping of the flywheel on the shaft. The generators were tested up to 2100 rpm, but without surge loading. At higher rotation speeds the centrifugal force increases and this leads to a decrease of the adhesion force which fixes the flywheel on the shaft. At the same time the loading moment at the beginning of the pulse increases, i.e. the peripheral force at the contact point of the shaft and the flywheel. Thus there is a risk of flywheel slipping. Because of the lack of data, it was not possible to estimate the maximum possible operational rotation speed. Therefore, calculations were performed with the assumption that the rotation speeds can be increased to 1750 rpm and with the assumption that the unit should be able to withstand loading even at 1800 rpm.

There are not these problems when lowering the operational rotation speed. Unfortunately, the available energy is increasing slowly with lowering this limit. The further disadvantage is longer time necessary to increase rotation speed back to the initial operational rotation speed. The decrease of the rotation speed to 1100 rpm was considered in this study.

The calculations showed that the transferred energy 70 MJ can be achieved from each of the generators with rotation speed range 1750/1100 rpm. Therefore, there is also a modest energy reserve consisting of possibility to start the rotation speed at 1800 rpm and at the other limit to end the rotation speed down at 1000 rpm. Nevertheless, the 1750 rpm is on the safety side, i.e. not overloading the generators above the original design nominal parameters.

Furthermore, the possibility of increasing the output voltage from the generators from currently used 6 kV to 6.6 kV was discussed. Technically it is possible, the generator would be still within the tolerances and the power of the generators would be increased.

New Generators

Based on the Power Supply system requirements, it was specified that that the power of approximately 170 MW and energy approximately 340 MJ is required for the new tokamak. It is clear from the preceding text how the existing generators can be used from the energy point of view and it would be simple to specify the necessary power and energy of the new generators. Nevertheless, it is necessary to take into account the requirements of the individual windings from the point of view of power and energies. The existing generators were used with similar generated voltage and current, and with similar power load and transferred energy. Therefore, it is suitable to consider carefully the “ratio” of power and energy of existing generators, of new generators (when specifying their requirements) and their relation to the requirements of the individual windings. The key point is the decision about which winding will be powered from the existing generators. Only then the new generators can be specified.

The existing generators would satisfy the power requirements of the TF coils of the new tokamak, but the energy requirements are problematic. The TF coils need 140 MJ. If the change of the generator operation described above is performed (using rotation speed from 1750 rpm to 1100 rpm), then the required energy is achieved.

The PF windings of the new tokamak require energy 100 MJ, therefore, the two existing generators are sufficient, but the power requirement is 70-80 MW in pulse, which is a problem for the existing generators.

The next considered factor is the voltage waveform at the output from the generators during the pulse. The existing generators would be “softer” than the new more powerful generators and, therefore, the voltage would decrease faster. This is more acceptable for the Toroidal Field winding than for the Poloidal Field windings.

Based on the listed reasons, the two new generators with pulse power 80 MW (each) and usable energy 100 MJ (each) were considered. The existing generators will supply the TF coils, the new generators will be used for the PF coils and additional heating systems.

The definition of the new generators corresponds approximately to the medium option introduced above. The minimal option would not bring the required power, i.e. it would be borderline, without any reserves. It is necessary to note that the simulations do not calculate with detailed losses on power lines, converters and transformers. Furthermore, the discussions with the potential manufacturers resulted into conclusion that the generator with “only” lower power rating does not provide significant cost savings. Conversely, the significantly higher ratings of the generators (both in the energy and in the power – see the large option) would dramatically increase the cost of the generators in the order of tens of millions CZK. The machines would be so large that the number of possible (worldwide) manufacturers would be limited with respect to their technological capabilities.

It is necessary to mention the problem of the energy recuperation in the connection with the generators. The existing tokamak has a minority of the energy in the magnetic field and a majority in the ohmic losses. The energy from the magnetic field is, therefore, dissipated in the ohmic losses during the current ramp-down.
In the new tokamak the energy usage will be opposite, i.e. approximately 2/3 of the energy in the magnetic field and approximately 1/3 of the energy in the ohmic losses. Therefore, the energy from the magnetic field will not be dissipated in the ohmic losses, but it will be recuperated. It concerns primarily the energy from the TF coils. Based on the agreement with the IPP, the energy from the PF coils will not be recuperated. Therefore, this issue is connected to both the generators and the TF coils converters.

To be complete, it is necessary to mention that other options of ensuring the required energy for the tokamak pulses (i.e. accumulation before the pulse) were also considered. The main considered option was an installation of ultracapacitors. Though, this option has significant disadvantages, therefore the option was rejected and the financial calculation was not performed.
The disadvantages are:

- The ultracapacitor manufacturers do not guarantee longevity with required type of power loads. Generally, it is valid that the generators are significantly more robust and more resistant.
- Longer charging durations, therefore, the accumulation of energy.
- Large installation area (this point was not solved exactly).
- The major disadvantage is that the ultracapacitors are a power source with large internal impedance and, therefore, it is a “soft” source which is not usable for tokamak needs, i.e. it would need massive oversizing.

5. Toroidal Field Coils Power Supplies

Circuit characteristics

The TF field winding circuit is completely electrically separated from other tokamak circuits, it has no mutual inductive coupling with other circuits. It represents the largest energy load of the whole system.

The current waveform in the winding can be split into three phases (see Figures 5 and 2):

- The maximal Power Supply voltage is applied to the winding, the current in the winding rises with a slope of approximately di/dt = U/L (the Power Supply voltage is approximately four times larger than the value corresponding to a stationary current without control – the ohmic component is negligible). The requested value of the current is reached after approximately 1 second.
- After reaching the requested value of the current the Power Supply transitions to a regime of active feedback control maintaining a constant value of the current.
- After a requested period of time (1 s for the original tokamak and for the new tokamak) the Power Supply is turned off and the current on the load can dissipate through a zero diode with the characteristic L/R time constant of the circuit.

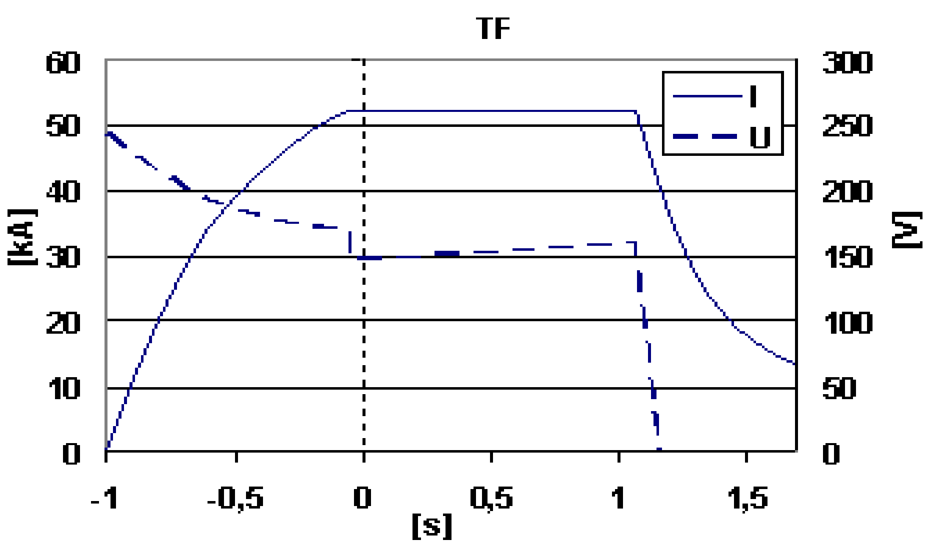


Figure 5 – Requested current waveform in the TF winding for the original installation. In the new installation the current waveform will be similar with longer times and different electrical parameters.

Power Supplies for the Toroidal Field coils

The utilization of all existing converter units with thyristors is expected for this Power Supply. There are 16 converter blocks (in 6-pulse bridge arrangement) available in the present installation of the TF Power Supply and altogether 10 blocks are installed for the PF coils Power Supplies. The total number of the rack cabinets is 16, i.e. 26 thyristor blocks.

As was suggested above, the existing generators would be used for powering the TF coils. All the existing thyristor Power Supplies (for present TF and PF) would be used for powering the Toroidal Field coils of the new tokamak. It would be necessary to complement this Power Supply with three additional rack cabinets for the requested power of the new installation, thus 6 thyristor blocks. It is evident that it would be fitting that the added blocks had the same design. Only the used components (thyristors) would be changed. They are currently fitted with thyristors of the TV 989-2700-28 type from the production of the then company Polovodiče a.s. (today ABB). We propose to use adequate thyristors of the 5STP 27H2801 type from ABB (replacement for the original thyristors from Polovodiče a.s.) for the new blocks. It would not be necessary to change the thyristors in existing blocks in that case. It also seems inefficient to replace all thyristor converters with IGBT based converters, alternatively to complement them with IGBT based converters.

The situation is similar as with the existing generators in the case of the converters for the TF coils – the optimal option seems to be maximal utilization of existing devices which are able to fulfil their purpose and are not obsolete.

To thyristor Power Supplies also points the fact that TF coils do not require feedback control, current changes are slow and can be pre-programmed. Therefore, from a technical standpoint fast IGBT converters are not necessary.

As was stated above, converters for TF coils will in comparison with the present state also serve for recuperation of energy from the magnetic field of the Toroidal Field winding back into the generator. This will have to be taken care of within the generator and the start-up engine control in order to prevent needles impacts in the generator which would be a problem mainly for the clutch. It is important that the existing technology enables that and specific adjustments in control will be the subject of the actual realization.

The schematic of the new solution for the Power Supplies for the TF coils is in Annex 1 where the original thyristor blocks are drawn in black and the new ones in blue.

Current dimensioning of the thyristors and thereby the verification of their viability for the new tokamak with a pulse duration of 3 seconds was checked by measurement of warming on the current device and a subsequent calculation.

Transformers for Toroidal Field coils

The toroidal winding of the new COMPASS-U tokamak requires for the achievement of the necessary current ramp-up slope higher initial voltage on the Power Supply. For this reason, it is necessary to change the parameters of the Power Supply transformers – a nominal output voltage of 600 V is requested. Due to the higher inductance of the tokamak coils it would be possible to use even 12-pulse converters (with higher ripple) instead of 24 pulse ones. Therefore, transformers can be of the two-winding type in e.g. Y/y and D/y arrangements. Existing transformers are of the three-winding type with a zig-zag arrangement on the secondary side.

Present transformers would be sufficient in terms of their power, but they have a different secondary voltage and most importantly quite large losses which negatively impact energy balance. The existing transformers could be theoretically used after their reconstruction – replacement of the secondary coil – for one thing due to the different voltage and above all to use Cu windings. The present ones have in fact Al windings. The existing transformers are of the DTTHDG 4000/6 type and are labelled as T3A and T3B.

The options for the solution for transformers are therefore:

- Reuse 2 existing transformers + add 2 new transformers with the same (enhanced) parameters.
- Supply 4 new transformers of the same power rating as the existing ones, but with lower losses.
- Another option is to supply 2 three-winding transformers, but with double the power in comparisons to the existing ones and again with lower losses.

Considering the prices of transformers, the option n. 1 appears as the most economically advantageous (with reconditioning of existing transformers), but the price offers from suppliers did not correspond to that. The option with two three-winding transformers in turn leads to overly large transformers. Therefore, for the final variant 4 new two-winding transformers are considered.

Source Materials for the Calculation

The source materials for the calculation are cited in this part in order to make it clear how the indicative prices for individual Power Supply system components were reached.

The toroidal coils circuit with the utilization of the existing installation can be designed thusly:

1) Toroidal coils consist of two identical sections. Each section is powered by a twelve pulse rectifier assembled from 8 existing rack cabinets. It is necessary to build 3 new such rack cabinets for the completion of the circuit. The new rack cabinets will use 36 pcs of thyristors (suggested type 5STP 27H2801 from ABB).
2) It is necessary to include choke coils in the price calculation, even though it is not clear whether they will be necessary. Verification will be necessary once transformer parameters will be known for their potential use. The possible choke coils would have similar parameters to the existing ones, the current load would be doubled. At least two times increase of the cross-section against the existing choke coils is assumed due to the requirement to lower the losses.
3) 4 transformers of the same power rating as the present ones for powering the thyristor blocks. The reasons for this transformer option were given above.

Indicative transformer parameters (determined from present ones, but converted to Cu winding):

- power 4000 kVA (24 MVA for a duration of 3s)
- 6 000 / 600 V, AN
- Po = 5 500 W, Pk = 30 000 kW
- impedance = 5 % for 4 MVA
- total mass approximately 8500 kg

6. Poloidal Field Coils Power Supplies

Power Supplies for the Tokamak Poloidal Field Windings and Possible Solutions

The new tokamak will have 14 independently powered coils for the creation of the Poloidal Field.

The individual coils can be divided according the following parameters:

- according to the maximal current: 50 kA or 30 kA
- according to the maximal required voltage: 800 v or 400 V
- according to the polarity of current and voltage: two-quadrant (one current polarity) or four-quadrant

In general, two concepts can be used to implement the converters supplying the individual PF coils. These concepts are either thyristor based converters or IGBT transistor based converters. Each of the concepts has its own advantages and disadvantages. The IGBT converters are indeed more modern technology, they allow higher switching frequency (against the basic one of thyristors) and, therefore, they have faster response of the control. The advantage of the thyristor converters is significantly lower price for the semiconductor components, but the lower price may be "balanced" by a price of the transformers (one transformer for each converter). At the beginning of the study preparation it was not clear which concept is more advantageous, therefore, both options were evaluated. The possible third option would be a combination of both types of converters, where the "shaping" coils would be supplied by thyristor converters (the response time is not so critical) and other coils would be supplied by IGBT converters. This option was supposed to be evaluated only after evaluation of the first two options.

The TF coils Power Supplies did not require the decision, because it is clearly more economical to utilize the existing thyristor converters and thus only their supplementation by additional thyristor converters.

Power Supplies Option with Thyristor Converters

Considering the fact that each Power Supply (for each PF coils winding) must be controlled independently, then each Power Supply must consist of particular converter and supplying transformer. The transformers are the three-winding type, with two secondary windings, and there is a 12-pulse converter supplied from them. The purpose of this configuration is to lower the current ripple. The four-quadrant Power Supplies will use dual (anti-parallel) 12-pulse converters (controlled) without circling currents ("reverzační 12-pulzní usměrňovač bez okruhových proudů" – one of the converters is always blocked, allowing operation without

DC chokes). A similar solution of the thyristor parallel operation as used for the existing Power Supplies, but without choke coils at the output, is assumed.

A single-line diagram schematic of the converters for the PF coils is in Annex 2.

The converters were drafted based on the requested currents for the individual PF coils.

The following thyristors were selected for converters calculations based on currents and voltages:

- type 5STP 45N2800 (ABB) with parameters

  V_{DRM} = 2800 V

  $I_{T(AV)M}$ = 5080 A

  $I_{T(RMS)}$ = 7970 A

  I_{TSM} = 77.0 kA

  V_{T0} = 0.86 V

  r_T = 0.07 mΩ

- type 5STP 45Q2800 (ABB) with parameters

  V_{DRM} = 2800 V

  $I_{T(AV)M}$ = 5490 A

  $I_{T(RMS)}$ = 8625 A

  I_{TSM} = 77.0 kA

  V_{T0} = 0.86 V

  r_T = 0.07 mΩ

- type 5STP 50Q1800 (ABB) with parameters

  V_{DRM} = 1800 V

  $I_{T(AV)M}$ = 6100 A

  $I_{T(RMS)}$ = 9600 A

  I_{TSM} = 94.0 kA

  V_{T0} = 0.9 V

  r_T = 0.05 mΩ

The following table shows basic parameters for individual Power supplies for individual PF windings.

Table legend:

- Q – number of quadrants (and converters) for given winding
- U – voltage

- I – current
- TYR. TYPE – selected thyristor type
- TYR. count – the number of thyristors for all converters for given winding (Power Supply)

Basic parameters of the Power Supplies for the PF windings – thyristor option:

	Supply	Q	U [V]	I [kA]	TYR. TYPE	TYR count
1	**CS1U**	4	800	50	5STP 45N2800	48
2	**CS1L**	4	800	50	5STP 45N2800	48
3	**CS2U**	4	800	50	5STP 45N2800	48
4	**CS2L**	4	800	50	5STP 45N2800	48
5	**CS3U**	4	800	50	5STP 45N2800	48
6	**CS3L**	4	800	50	5STP 45N2800	48
7	**PF3U**	2	800	30	5STP 45Q2800	12
8	**PF4U**	2	800	30	5STP 45Q2800	12
9	**PF4L**	2	800	30	5STP 45Q2800	12
10	**PF1U**	2	400	30	5STP 50Q1800	12
11	**PF1L**	2	400	30	5STP 50Q1800	12
12	**PF2U**	2	400	30	5STP 50Q1800	12
13	**PF2L**	4	400	30	5STP 50Q1800	24
14	**PF3L**	2	400	30	5STP 50Q1800	12

There are calculated parameters of the transformers for the Power Supplies in the preceding table in the following table:

	Supply	U2 [V]	Smax [MVA]
1	**CS1U**	593	40
2	**CS1L**	593	40
3	**CS2U**	593	40
4	**CS2L**	593	40
5	**CS3U**	593	40
6	**CS3L**	593	40
7	**PF3U**	593	24
8	**PF4U**	593	24

	Supply	U2 [V]	Smax [MVA]
9	**PF4L**	593	24
10	**PF1U**	296	12
11	**PF1L**	296	12
12	**PF2U**	296	12
13	**PF2L**	296	12
14	**PF3L**	296	12

Table legend:

- U2 – secondary voltage of the transformer.
- The source transformers are three-phase, three-winding type with primary voltage 3x 6000 V and with secondary voltage 2x3x U2 according the table.
- There is the transformer required peak apparent power Smax, for pulse of the length 3 seconds, denoted in the table.
- The U2 is the required voltage on the secondary transformer winding when loaded with “average” load. Open circuit voltage will be approximately 1.15x higher.

Power Supplies Option with IGBT Converters

This option assumes usage of the pulse voltage converters constructed on the basis of IGBT. The power source circuits would consist of three-winding transformer, 12-pulse diode rectifier, voltage DC-link with capacitor bank. The IGBT pulse converters in the bridge connection would be connected to the DC link.
The basic difference against the thyristor option is that the input circuit (up to the DC link with capacitor bank) would be common for all of the Power Supplies with identical voltage level. There will be two input circuits because it is advantageous to select DC voltage 400 V for some converters and 800 V for the second group. The voltage is selected with respect to the voltage classes of the commonly available IGBT modules.
A single-line diagram schematic of the converters for the PF coils is in Annex 3.

The particular semiconductor components (here IGBTs from the Infineon company) were selected for the purpose of the converter dimensioning for the following orientation calculation, in a similar process as in the case of thyristor option. The dimensioning was verified using SW IPOSIM from the Infineon company.

The selected IGBT modules (IGBT + integrated diodes) are: type FZ3600R17HE4 (for input voltage 800 V) and type FZ3600R12HP4 (for input voltage 400 V).

The basic parameters of the IGBTs:

- type FZ3600R12HP4
  - V_{CES} = 1200V
  - $I_{C\ nom}$ = 3600A / I_{CRM} = 7200A
  - E_{on}+$E_{off,125°C}$ = 1490 mJ
  - $R_{G,on}$ = 0.47 Ω
  - $R_{G,off}$ = 0.68 Ω
  - R_{thJC} = 0.0080 K/W
  - R_{thCH} = 0.0065 K/W
  - T_{vjmax} = 175 °C
- FZ3600R17HE4
  - V_{CES} = 1700V
  - $I_{C\ nom}$ = 3600A / I_{CRM} = 7200A
  - E_{on}+$E_{off,125°C}$ = 2300 mJ
  - $R_{G,on}$ = 0.47 Ω
  - $R_{G,off}$ = 0.68 Ω
  - R_{thJC} = 0.0072 K/W
  - R_{thCH} = 0.0063 K/W
  - T_{vjmax} = 175 °C

The basic parameters of the diodes:

- $E_{rec,125°C}$ = 345.00 mWs
- R_{thJC} = 0.0326 K/W
- R_{thCH} = 0.0115 K/W
- T_{vjmax} = 150 °C

The parameters of the simulated test:

- Input Voltage 800 V
- Blocking Voltage 1700 V

- Output Voltage 600 V
- Duty Cycle 0.81
- Switching Frequency 500 Hz
- Output Current 1600 A
- Number of cycles 5

The resulting temperature waveform is shown in Figure 6. It is obvious that the components will accommodate the requested current load. The simulation shows that the temperature reaches 146°C when the allowed temperature is 150°C. The simulation was performed for 5 cycles (pulses with 3 seconds duration) consecutively, but the real operation has a significant time delay between the pulses. Therefore, the components meet the requirements with reserves.

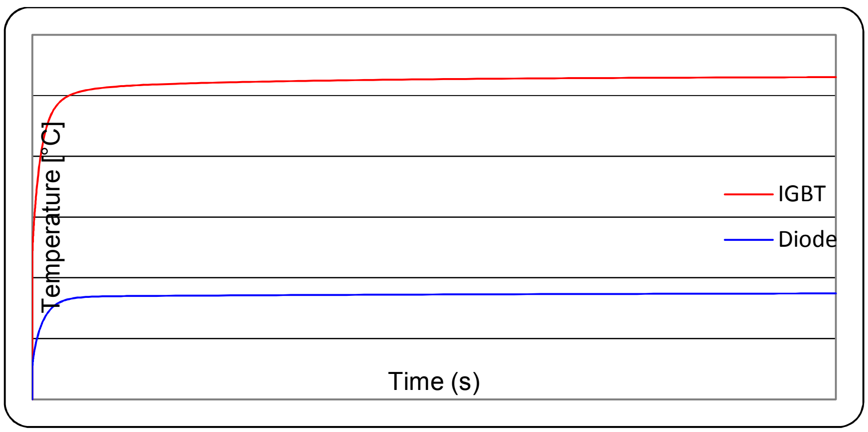


Figure 6 – Simulation of the temperature waveform on the IGBT and on the diode for the requested current load.

The specification of the semiconductor components for the converters of the individual Power Supplies was prepared for the purpose of the orientation calculation. The following table states the component type and quantity for the given Power Supply.

Table of the converter setup with INFINEON components:

	Supply	IGBT TYPE	IGBT count	DIODE TYPE	DIODE count
1	CS1U	FZ3600R17HE4	68	-	-
2	CS1L	FZ3600R17HE4	68	-	-
3	CS2U	FZ3600R17HE4	68	-	-
4	CS2L	FZ3600R17HE4	68	-	-
5	CS3U	FZ3600R17HE4	68	-	-

6	CS3L	FZ3600R17HE4	68	-	-
7	PF3U	FZ3600R17HE4	20	DD1200S17H4_B2	60
8	PF4U	FZ3600R17HE4	20	DD1200S17H4_B2	60
9	PF4L	FZ3600R17HE4	20	DD1200S17H4_B2	60
10	PF1U	FZ3600R12HP4	18	DD1200sS12H4	60
11	PF1L	FZ3600R12HP4	18		60
12	PF2U	FZ3600R12HP4	18		60
13	PF2L	FZ3600R12HP4	36	-	-
14	PF3L	FZ3600R12HP4	18		60

Furthermore, it was necessary to specify the entire input circuit, or at least the basic components with the important cost influence, for the purpose of the financial calculation.

These are, primarily, the transformers, key components for the rectifiers and capacitors for the DC link.

Regarding the transformers, the sources (i.e. 2 insulated DC links) will be powered by two three-phase, three-winding transformers. The nominal input voltage is 3x 6000 V for both of them. The secondary winding of the first one is 2x3x300V (for the converters with DC link 400 V) and of the second one it is 2x3x 600 V (for converters with DC link 800 V). The peak transferred power must be dimensioned to 100 MVA for each of the transformers (including supply for auxiliary heating systems). The transformers are loaded with a 3 seconds long pulse and then there is 15 minutes long period without voltage.

There is a 12-pulse diode rectifier for each converters section after the transformer. Therefore, there are two input rectifiers. The diodes SDD60Q2800 were selected for the purpose of the dimensioning. It was not the purpose of this study to create the particular technical and construction solution. Nevertheless, for the purpose of the calculation it was determined from the necessary power for all Power Supplies, that the input rectifiers will be constructed from 162 pieces of the stated diodes.

The next part of the circuit is the DC link, in this case 2 different DC links, one for 400 V, second for 800 V. The principal component of the DC link are the capacitors for stabilization of the voltage.

Indicative Comparison of Options

As was stated in the introduction of this chapter, the comparison of the options with thyristor and IGBT converters will be possible only on the basis of the economical calculation. Nevertheless, it is already apparent that the solution with the thyristor converters is problematic at least from the point of view of the necessary space, because 14 transformers for the individual Power Supplies would occupy more space than two (even though) large transformers necessary for the IGBT option.

Another issue which should be solved for the transformers is the transformer type from the point of view dry-type or oil-type. The thyristor converters would certainly use dry-type transformers. The type of the 100 MVA transformers for the IGBT converters option was not fully resolved. It is probable that it will be problematic to manufacture such transformer, according to the orientation calculations from the transformer manufacturers, even though it is not impossible. This will be a part of the detailed calculations in the case of actual realization. It would be easier to manufacture the oil-type transformer, where the dimension is not a problem, but this option has its own ecological problems, specifically for the housing which would require sufficiently large oil reservoirs and appropriately adapted transformer space.

From the technological point of view, the IGBT converters are more advantageous because these allow fast current changes.

7. Economical Calculation

The chapter is confidential and it was removed from the published material.

8. Conclusion

The goal of the study was to map the possibilities in the solution of the Power Supply system for the new COMPASS-U tokamak. We consider the goal to be fulfilled. The different options of the Power Supply system solutions, i.e. its parts which are primarily flywheel generators, transformers and converters, were examined. The price estimations for the individual parts of the Power Supply system, or even for the individual options of the technological solutions, were obtained. The reference solution of the power source part was selected, based on the price estimations.

The optimal solution appears to be:

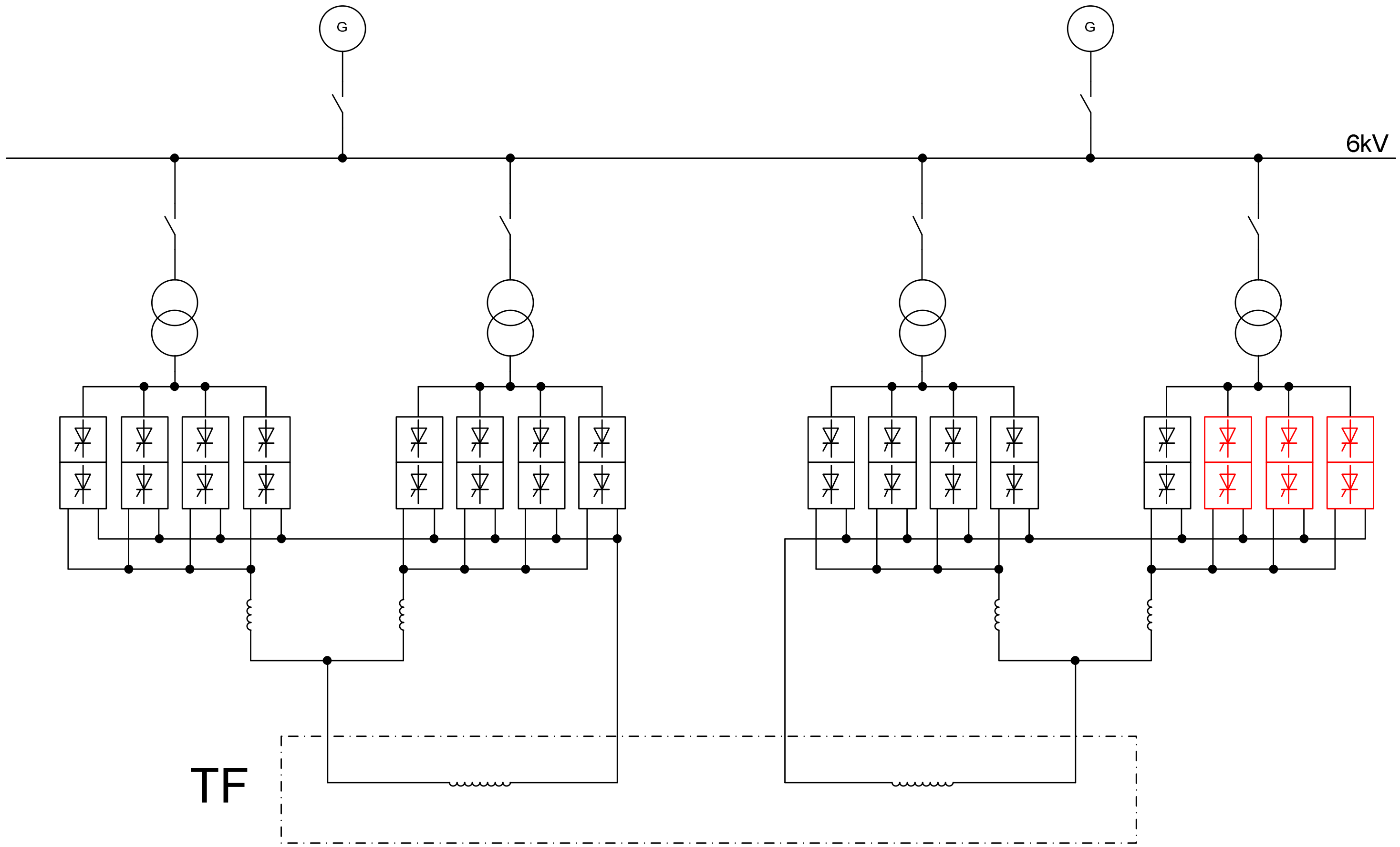
- Optimize the operation of the existing flywheel generators by increase in the rotation speed range with the intention of increased usage of the accumulated energy.
- Supplement the Power Supply system with two new flywheel generators in the “medium” option, i.e. 90 MVA (for duration 3 s), 100 MJ each.
- Use the existing flywheel generators for the supplying of the Toroidal Field winding. The generators would work in parallel and they would supply only this winding.
- Use the existing thyristor converters for the shaping of the supply of the Toroidal field winding. Supplement the converters with 6 new identical thyristor blocks.
- Install 4 new transformers for the Power supplies of the TF winding.
- The new generators would be used for supplying the other devices, i.e. Poloidal Field windings and additional heating systems.
- Build the new converters based on the IGBT transistors for the Poloidal Field windings. These converters will be supplied from common two DC links.
- Install 2 new large transformers for the PF coils Power Supplies.

The orientation price for the stated configuration is deleted million CZK. It should be noted that this is an expert estimation, not exact price. From the previous chapter it is obvious, in which parts the price is more or less exact.

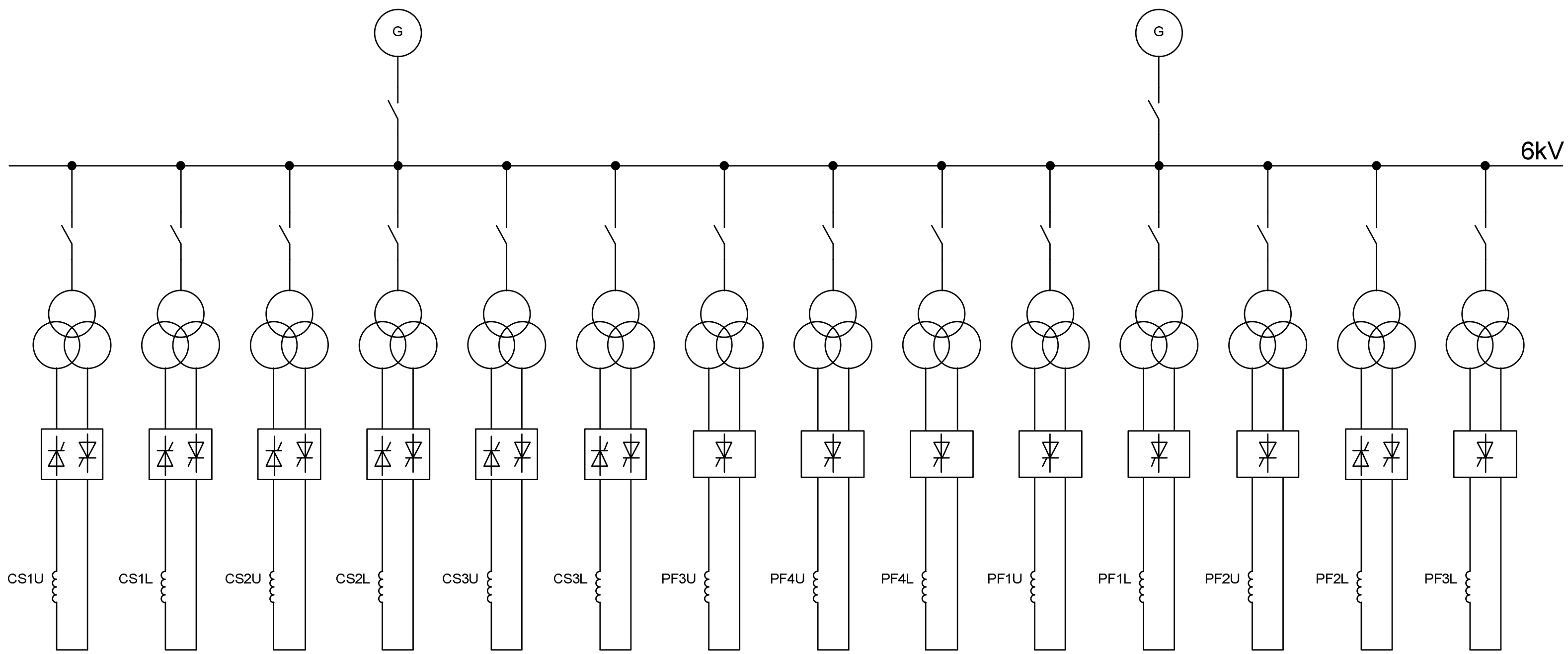
As the final remark it should be stated that in this phase the project has too many degrees of freedom, which significantly complicates finding the real optimal solution from both technological and financial point of view. It was not possible within the scope of this study to create a detailed technical and economic analysis for all options and their combinations. Therefore, it is recommended for the next phase of the project to first fixate the technological parameters, which have the most significant influence on the cost, and based on this then compile more detailed options for solutions in the follow-up parts.

Annexes

Annex 1 – Schematics of the new solution for the TF coils Power Supplies (black colour for the existing thyristor blocks, red colour for the new ones).



Annex 2 - A single-line diagram schematic of the converters for the PF – thyristor option



Annex 3 - A single-line diagram schematic of the converters for the PF coils – IGBT option