TPX Power Systems Design Overview

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ABSTRACT

The power systems for the Tokamak Physics Experiment (TPX) supply the Toroidal Field (TF), Poloidal Field (PF), Field Error Correction (FEC), and Fast Vertical Position Control (FVPC) coil systems, the Neutral Beam (NB), Ion Cyclotron (IC), Lower Hybrid (LH) and Electron Cyclotron (EC) heating & current drive systems, and all balance of plant loads. Existing equipment from the Tokamak Fusion Test Reactor (TFTR), including the motor-generator (MG) sets and the rectifiers, can be adapted for the supply of the TPX PF systems. A new TF power supply is required. A new substation is required for the heating & current drive systems (NB, IC, LH, and EC). The baseline TPX load can be taken directly from the grid without special provision, whereas if all upgrade options are undertaken, a modest amount of reactive compensation will be required. This paper describes the conceptual design of the power systems [1], with emphasis on the AC, TF, and PF Systems, and the quench protection of the superconducting coils.

INTRODUCTION

The TPX is an advanced, steady state tokamak experiment to be built at the Princeton Plasma Physics Laboratory (PPPL). It will be the first tokamak to utilize superconducting coils for both the TF and PF. Baseline operation requires a duty cycle with a 1000 second plasma burn pulse repeated once every 4500 seconds. The following upgrade options have been identified and considered in the design, but only to the extent required to demonstrate feasibility:

Option I:	Single Null Plasma Operation
Option II:	Increased Heating & Current Drive Power
Option III:	Quasi-continuous Plasma Operation

Although the TPX utilizes superconducting TF and PF coils, and the power demand of the continuously operated TF system is small, the demand of the PF system is large during plasma ramp up/down. The demand of the heating & current drive systems is large. The overall electrical demand of TPX is smaller than, but of the same order of magnitude as, the TFTR.

In addition to the basic issues related to the supply of power, the protection of the superconducting coils is of critical importance. In the event of a quench, the stored magnetic energy must be rapidly removed to avoid overheating.

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AC POWER SYSTEM

The major experimental power loads consist of the PF system and the heating & current drive systems [2]. Additional loads consist of the PPPL facility conventional loads, plus those associated with the TPX auxiliary systems (TF, cryogenic system, and all additional loads). For the upgrade options, it is assumed that no additional power is demanded by Option I, while option II requires an increase in heating & current drive power, and option III is assumed to demand the same peak power as option II only for a longer duration. The approximate peak power levels are summarized in the following table.

Load	Baseline (MW/MVAR)	Option II/III (MW/MVAR)
PPPL Facilities	5/3.75	5/3.75
TPX Aux Sys	20/15	20/15
TPX PF (ramp)	75/*	75/*
TPX PF (burn)	10/*	10/*
NB/IC/LH/EC	66/34	197/102

* = reactive power determined by converter configuration

A study was undertaken to determine the best scheme for the AC supply. While it was obvious that the PPPL facilities, TPX auxiliary systems, and heating & current drive systems should be supplied directly by the grid, the choice for the supply of power to the PF system was not so obvious, and involved consideration of the design of both the AC and DC sides of the PF system. The following options were considered.

1. PF power from TFTR MG set using TFTR rectifiers during ramping and burn.
2. PF power from TFTR MG during ramping, from grid during burn, using TFTR rectifiers.
3. PF power from TFTR MG using TFTR rectifiers during ramping, and from grid using new rectifiers during burn.
4. PF power from grid during ramp and burn, using TFTR rectifiers, with reactive compensation.
5. PF power from grid during ramp and burn, using TFTR rectifiers during ramp and using new rectifiers during burn.
6. PF power from grid during ramp and burn, using new rectifier during ramping, and using new rectifiers during burn.

A major design driver is the need to match the rectifier characteristics to the demands of the load. During ramping a relatively high forcing voltage is required while during burn a very low voltage is required. For example, the existing TFTR rectifiers produce 1KV DC no-load with 13.8kV AC input voltage, which is a suitable level for ramping but not for the burn phase. If phase control is used to reduce the voltage during burn, then the controllability and power factor are poor. Design options available to overcome these difficulties are as follows:

- adjust AC supply voltage via MG excitation
- provide bus transfer between dual AC feed voltages
- use phase control with reactive compensation
- provide dedicated rectifiers for ramp and burn

An additional problem related to the last three but not the first of the above four schemes is the limitation imposed by the utility on reverse power flow.

After consideration of the performance characteristics and total life cycle costs (including initial equipment costs, MG maintenance costs, energy costs, demand costs, interruptable credits, etc.) of the six major options identified for the PF power supply, and after careful evaluation of the remaining operating life available from the TFTR equipment, the first option was selected, namely that the PF system is to be powered using the existing TFTR MG sets and rectifiers. The advantages of this selection include the following:

- continuous adjustability of full scale rectifier output voltage via MG excitation to match supply to load
- buffer between dynamic load and grid; no reverse power flow to grid
- peak power demand from grid within existing capabilities for baseline load, modest reactive compensation required for Option II.
- minimal changes to TFTR MG and AC distribution to rectifiers
- minimum life cycle cost.

A simplified one line diagram of the AC system is shown in figure 1.

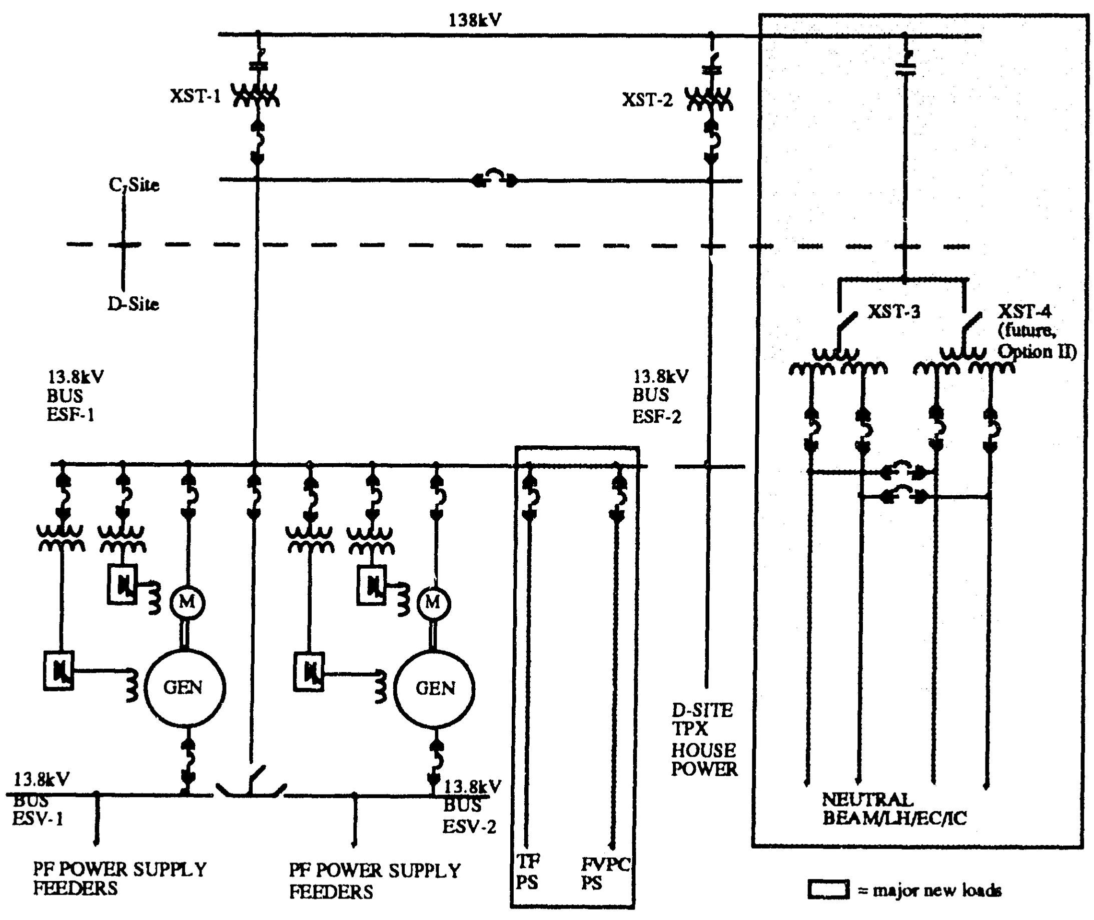

Fig. 1 Simplified One Line Diagram of TPX AC Power System

A new 138kV transmission spur roughly 1000 feet long is required to bring power from the existing C-Site substation to the new substation located at D-Site. For the baseline, only one new transformer (XST-3) is required. For Option 2 a second transformer (XST-4) is added, and reactive compensation will be required to limit voltage flicker. With the TFTR MG set (only one of two units is required) acting as a buffer between the TPX PF load and the grid, the total load imposed is as follows:

Load	Baseline (MW/MVAR)	Option II/III (MW/MVAR)
Base	31/24	31/24
Pulsed	66/34	197/102
Peak	97/58	228/126

Preliminary calculations performed in conjunction with Public Service Electric & Gas (PSE&G) indicate that 50 to 100MVAR of compensation will be required for Option II.

TF SYSTEM

The basic parameters and requirements of the TF system are summarized in the following table.

Maximum Field	4 Tesla
Inductance	1.824 Henries
Maximum Current	33.48 kA
Maximum Energy	1.022 GJoules
Ramp Up/Down Time	10 minutes (600 seconds)
No-load Ramp Voltage	120 volts
No-load Hold Voltage	10 volts
Maximum Quench $\int i^2(t)dt$*	2.7×10^9 amp^2-sec
Peak Quench Dump Voltage	12.5kV

* = after allowance for 1 second quench detection time

The following topology options were considered:

1. Single voltage power supply
2. Dual voltage power supply, one converter, bus transfer between primary feed voltages
3. Dual voltage power supply, two converters, two converter transformers
4. Dual voltage power supply, two converters, single converter transformer with tapped secondary

The following control options were considered:

1. AC-side Pulse Width Modulated (PWM) thyristor control, diode DC rectifier
2. DC-side PWM thyristor control, thyristor DC rectifier
3. AC-side thyristor phase control, diode DC rectifier
4. AC-side induction voltage regulator, diode DC rectifier
5. AC-side thyristor phase control and induction voltage regulator, diode DC rectifier
6. DC-side thyristor phase control, thyristor DC rectifier

The following rectifier configurations were considered:

1. Six pulse bridge rectifier
2. Six pulse midpoint star connected rectifier

The major design drivers were as follows:

• high voltage during ramp versus low voltage during hold
• inversion requirement during ramp down
• controllability during hold mode
• harmonic content on AC and DC sides
• reactive power consumption

As shown in figure 2, the selected configuration for the TF power supply is a single voltage, twelve pulse thyristor rectifier with freewheeling diode, consisting of a pair of parallel connected six pulse bridges with individual freewheeling diodes. This selection was made after analysis was performed which showed that, because of the large inductance of the TF coils, the harmonic content of the DC current is insignificant, and the controllability is quite adequate even with the 120V converter running at a low average voltage in the hold mode. In addition, with a freewheeling thyristor, the reactive power consumption in the hold mode is minimal. Since the performance of this scheme is adequate and its cost is probably the lowest amongst the viable options it was chosen as the preferred one.

For quench protection, a DC circuit breaker (DCCB) technology consisting of explosivly actuated breakers was chosen. The rationale for this selection is described later. For the dump resistor, the use of high and low temperature coefficient of resistance (TCR) resistors is envisioned. With this scheme, the discharge voltage during a quench protection (QP) event can be tailored to minimize the peak voltage required to remove the coil energy within a given $\int i^2(t)dt$ constraint.

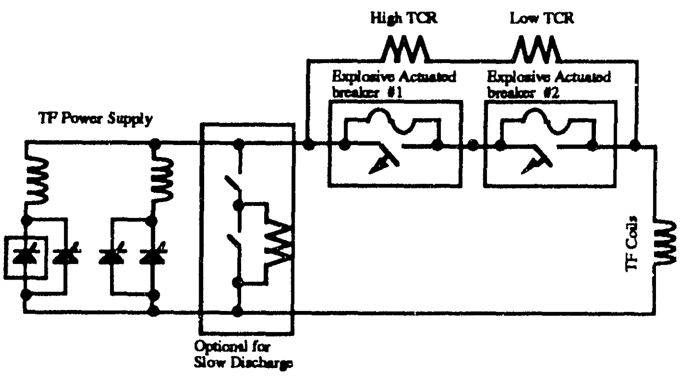

Fig. 2 Simplified Schematic of TF System

PF SYSTEM

There are seven pairs of upper and lower PF coils, each of which will be powered by a dedicated power supply circuit. In the baseline, the currents in the upper and lower coils are to be identical, while in the single null mode (Option I) a difference current is required. Each of the seven PF circuits has unique requirements in terms of current profile, plasma initiation (PI) voltage, and quench protection (QP) $\int i^2(t)dt$ limit. The worst case requirements are summarized in the following table:

Peak current	27.0kA
Maximum Sustained Current	25.4kA
Peak Plasma Initiation Voltage	6.0 kV
Quench $\int i^2(t)dt$*	1.2×10^9 amp^2-sec

* = after allowance for 1 second quench detection time

An analysis was performed to determine the capability of the TFTR rectifiers for TPX duty, and it was found that, for 1000 second pulses, a current of 6kA could be sustained. A simulation [3] was developed to investigate the operation of the TFTR rectifiers and MG sets in the TPX mode, and it was determined that this equipment could be adapted for TPX duty by connecting TFTR rectifier sections in series and parallel in each PF circuit. A sufficient number of sections are available such that the ampacity required in both the positive and negative polarities can be provided using anti-parallel connected strings, without reversing switches. In addition, via adjustment of the MG excitation, the full scale voltage of the rectifiers can be tailored to the differing requirements of the ramp up/down and burn phases of the discharge.

A simplified schematic of a typical PF circuit is shown in figure 3.

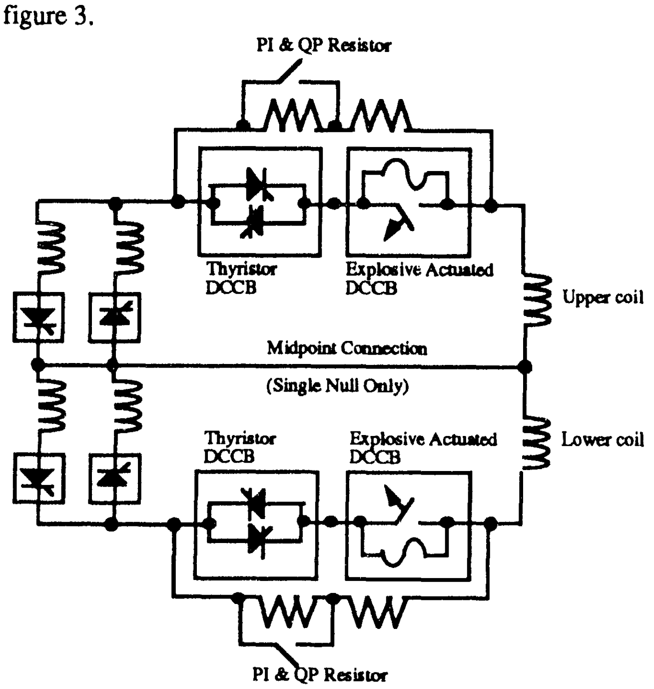

Fig. 3 Simplified Schematic of Typical PF Circuit

The midpoint connection and lower set of branch inductors are only required for the single null (Option I) upgrade. The number of series power supply sections is constrained to be an even number so that the strings can be split in half as shown for single null.

For the PI and QP functions, both the counterpulsed thyristor and explosivly actuated DCCB technologies are utilized, with the former used for PI and primary QP, and with the latter for back-up QP. The rationale for this selection is discussed later. Because in some cases the resistance to be inserted during PI is not compatible with QP, a shorting switch is required across a portion of the dump resistors.

For quasi-continuous operation (Option III) additional steady state low voltage, high current power supplies (not shown on figure 3) can be installed in shunt with the main power supplies to take over operation during an extended (>1000 sec) plasma burn.

QUENCH PROTECTION

A detailed study was performed [4] to identify the functional, topological, and technological QP options and to select baseline concepts for the TF and PF applications. The following DCCB technology options were considered:

1. Counterpulsed thyristor
2. GTO thyristor, continuous conduction
3. GTO thyristor, cyclic conduction
4. Counterpulsed vacuum breaker
5. Passive commutated gas blast breaker
6. Mechanical DC circuit breaker
7. Superconducting switch
8. Exploding switch
9. Exploding switch with shunt fuse
10. Thyristor, with shunt fuse in series with switched resistor

For the TF system, where the number of QP operations is expected to be minimal, the explosivly actuated breaker (consisting of exploding switch with shunt fuse) is viable and is selected as the least expensive and most reliable option. For the PF system, the explosivly actuated breaker is not viable for the PI function since this takes place every pulse. The counterpulsed thyristor breaker is suitable for PI but is not by itself sufficiently reliable for QP. Therefore the combination of the counterpulsed thyristor and explosivly actuated breakers are chosen for PF, with the former for PI and primary QP, and the latter as a back-up for QP.

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