AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

POWER SUPPLIES AND QUENCH PROTECTION FOR THE TOKAMAK PHYSICS EXPERIMENT

Charles L. Neumeyer
Raytheon Engineers & Constructors, EBASCO Division
P.O. Box 3148
Princeton, New Jersey 08540
(609) 243-2159

ABSTRACT

The Tokamak Physics Experiment (TPX) is an advanced tokamak project aimed at the production of quasi-steady state plasmas with advanced shape, heating, and particle control. TPX is to be built at the Princeton Plasma Physics Laboratory (PPPL) using many of the facilities from the Tokamak Fusion Test Reactor (TFTR). First plasma is scheduled for the year 2000.

TPX will be the first tokamak to utilize superconducting (SC) magnets in both the toroidal field (TF) and poloidal field (PF) systems. This is a new feature which requires not only a departure from the traditional tokamak power supply schemes but also that ultra-reliable quench protection devices be used to rapidly discharge the stored energy from the magnets in the event of a quench.

This paper describes the plan and basis for the adaptation and augmentation of the PPPL/TFTR power system facilities to supply TPX. Following a description of the basic operational requirements, four major areas are addressed, namely the AC power system, the TF power supply, the PF power supply, and quench protection for the TF and PF systems.

I. OPERATIONAL REQUIREMENTS

The design of the power systems is driven by the baseline requirements, and also by the possibility of several upgrade options which are foreseen.

A. Baseline Requirements

Plasma current	2 MA
Plasma configuration	Double Null
Toroidal Field	4 Tesla
Heating & Current Drive Power	17.5 MW
Max. pulse (burn) duration	1000 seconds
Min. repetition period	4500 seconds
Max. # pulses per 24 hours	10 pulses

B. Single Null Upgrade Option I

The plasma configuration is single null, which requires unequal currents in the upper and lower PF coils.

C. Heating & Current Drive Upgrade Option II

The heating & current drive (H&CD) power deliverable to the plasma is increased to 45 MW from 17.5 MW.

D. Steady State Upgrade Option III

A plasma is generated and driven in a quasi-steady state mode (several hours).

II. AC Power Systems

While the use of superconductors permits long pulse operation without undue power and energy demand by the magnets, the heating & current drive systems still present a substantial load over a long time period such that energy storage means are impractical, and the load must be taken directly from the utility grid. A summary of the peak values of the major loads is given in Table I. It is noted that in terms of peak load, Option I is identical to the baseline, and Options II and III are equivalent.

<u>Load</u>	<u>Baseline</u> (MW/MVAR)	<u>Option II/III</u> (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/*
H&CD (burn)	66/34	197/102

* = reactive power set by converter configuration

Table I - Summary of Peak Loads

Figure 1 - Simplified One-Line Diagram of TPX AC Power System

The existing TFTR power systems include two powerful (475 MVA, 2.25 GJ) motor-generator (MG) sets which deliver power to a large (1.8 GVA (pulsed) installed capacity) thyristor rectifier system. Analysis of the various options¹ for powering the magnet power supplies and the heating and current drive systems led to the conclusions that 1) the TF loads could be serviced through the existing substation transformers and a new rectifier, 2) the PF loads could be serviced by the TFTR MG systems and associated rectifiers, and 3) that the H&CD systems require a new substation and distribution system located immediately adjacent to the facility for the long pulse, high power load. Figure 1 shows a simplified one-line diagram of the AC power system.

The composite load imposed on the grid for the various stages of operation is summarized in Table 2.

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

Table 2 - Composite Load On Utility Grid

Preliminary calculations performed in conjunction with the local public utility indicate that 50 MVAR of reactive compensation will be required for Options II, and Option III may require the reconductoring of the transmission line spur which feeds the main 138 kV PPPL substation.

III. TF SYSTEM

The main parameters of the TF system are:

Maximum current (continuous)	33.5 kA
Field @ max. current, $r=2.25m$	4.0 Tesla
Inductance	1.8 Henries
Stored energy @ max. current	1.0 GJoule
Current ramp up/down interval	600 seconds
Maximum fast discharge voltage	15kV
Full load voltage (ramp)	115 volts
Full load voltage (hold)	10 volts

The TF system will nominally remain energized over the full operational day, but will occasionally be de-energized between pulses to permit glow discharge cleaning; this need dictates the ramping interval. Once the current is established, only the small voltage drop associated with the DC bus and rectifier semiconductor impedances needs to be provided. The fast discharge is obtained by resistor insertion and is reserved for emergency situations such as magnet quench events.

A simplified schematic of the TF circuit is given in Figure 2.

Figure 2 - Simplified Schematic of TF System

A. TF Rectifier Converter

A 12-pulse thyristor converter with fully rated bypass thyristor array, operable in the freewheeling mode, is envisioned. The reduction of primary voltage during current hold via AC bus transfer to an intermediate feeder transformer is being considered. This feature would reduce the reactive power and harmonics consumed by the converter during constant current (hold).

B. Interleaving

The DC circuit is divided into two interleaves to reduce voltage to ground during the 15kV fast discharge event to $\pm 3.75kV$ nominal, $\pm 7.5kV$ fault.

C. Converter Protection

A pulse rated closing switch is provided to provide a reliable discharge path for the magnet current in case the converter bypass thyristors in the rectifier converter become faulty. If this switch is closed, the fast discharge of the magnets must be invoked.

D. Quench Protection

In each interleaf a pair of DC circuit breaking devices, in parallel with an energy dump resistor, are provided. The main device provides the first line of defense for quench protection (QP) while the auxiliary device is a back-up. If a slow discharge is desired, then only one of the two resistors can be inserted; however this requires that each resistor be rated for the full energy.

IV. PF SYSTEM

The PF system consists of 7 pairs of coils with symmetry about the horizontal mid plane of the tokamak. For double null, the currents are identical in the upper and lower coils, whereas to create a single null, an asymmetry in the current is required in the PF-4, -5, and -6 coil pairs. Maximum parameters of the seven circuits are as follows:

Maximum current (instantaneous)	26.2 kA
Maximum current (1000 seconds)	24.1 kA
Stored energy @ max. current	50.4 MJoule
Maximum fast discharge voltage	10kV
Full load voltage (ramp)	1.4 kV
Full load voltage (burn)	TBD

During a pulse the PF coils are precharged, and then a resistor is inserted for the fast discharge for plasma initiation (PI). Once the plasma is established it is ramped

to its flat-top value and the "burn" phase commences. During burn, conditions are relatively quiescent; additional volt-seconds for plasma current drive are provided by the H&CD systems and plasma bootstrap effects. The voltage and power required during the burn, although small, is not specified at this stage of the design.

An additional benefit of the use of the TFTR MG sets as a power source for the PF conversion system is the capability for control of the AC voltage impressed on the converter transformers, via control of the excitation of the generator field winding. Using this feature the full voltage and power capability is available during the ramping phase, while the voltage can be reduced during the burn phase to better match the rectifiers to the requirements of the load.

A simplified schematic of a typical PF circuit is given in Figure 3.

Figure 3 - Simplified Schematic Diagram of Typical PF Circuit

A. PF Rectifier Converter

An anti-parallel connection of the TFTR rectifiers is provided for bipolar currents. The number of parallels in each current direction is tailored to the ampacity requirement of each circuit. The number of series layers is at least two, but in some cases (PF-6 and PF-7) four. A total of 66 of the 74 available 6-pulse bridges are used.

The remaining 8 are being reserved for use with internal control coils for fast plasma position control.

B. Midpoint Connection

For single null operation, PF-4, -5, and -6 include a connection from the midpoint of the coil pair to the midpoint of the power supply for difference current flow.

C. Converter Protection

A pulse rated closing switch is provided to provide a reliable discharge path for the magnet current in case the converter bypass thyristors become faulty. If this switch is closed, the fast discharge of the magnets must be invoked.

D. Plasma Initiation and Quench Protection

In each circuit one or two sets of DC circuit breaking devices, in parallel with an energy dump resistor, are provided, two sets in the case of those circuits with the midpoint connection. The main devices operates each pulse for PI, and provides the first line of defense for QP. The auxiliary device is a back-up. It is noted that, in the event of a QP event, all seven PF circuits are simultaneously discharged.

E. Blocking Diodes

Blocking diodes are located across a fraction of the dump resistor in those circuits whose maximum (-) current exceeds the maximum (+) current; in this way the maximum fast discharge voltage is limited to the value used for the PI function.

V. QUENCH PROTECTION

Quench protection (QP) is a critical function in both the TF and PF systems. In order to provide quantitative guidelines for the design of the QP equipment, reliability assumptions must be made. The failure of QP action has been classified as an "Unlikely Event" meaning that, should it occur, "The facility should be capable of returning to operation following potentially extensive corrective actions or repairs, as necessary". In accordance with this assumption the allowed probability (P) of occurrence is $10^{-1} > P \geq 10^{-3}$ over the life of the project. The tentative choice for the failure probability of the QP equipment (PQPF) is $\leq 10^{-2}$ over the life of the project. Assumptions concerning the number or actuations of the QP equipment, including trips due to spurious indications from the detection system, are as follows:

TF # of QP actuation events	15
TF # of actual quench events (TFQ)	5
TF # of QP devices (TFD)	2
PF # of QP actuation events	150
PF # of actual quench events (PFQ)	50
PF # of QP devices (PFD)	10

The above numbers for TF are roughly based on experience at Tore Supra and T-15, which have SC TF magnets. The PF numbers are not based on any actual experience since no tokamak with SC PF magnets exists. However it is recognized that the more dynamic magnetic

environment associated with the PF is likely to lead to more events.

Given the above assumptions for the actual number of quench events, and allowing for an equal failure probability for each QP device (PD), the allowable failure rate for each device, per event, can be calculated based on the following expression:

$$P = [TFQ \times TFD + PFQ \times PFD] \times PD \quad (1)$$

Accordingly, the allowed failure probability for each device is roughly 1 failure in 50000 events.

This failure rate is at least a order of magnitude lower than that achievable by traditional technologies used for DC circuit interruption, such as counterpulsed vacuum breakers or thyristor arrays. A study was undertaken to identify alternate means for satisfying these requirements². An alternate technology which, due to its inherent simplicity, has the potential for achieving the requisite reliability is the explosively actuated DC breaker. However, this class of devices is not practical for repetitive operation. In the TF system, operation of the DC breaker will be required not only for quench related events (actual quench events plus spurious trips) but also for the fast discharge of the circuit under other fault conditions. In the PF the PI event takes place every pulse. Therefore, to achieve the required reliability and to support repetitive operations a series combination of a repetitively operable device and the explosively actuated class of device is foreseen.

In the TF system, since relatively few operations are expected, a high current switch in parallel with a pair of series connected mechanical DC breakers will be connected in series with the explosively actuated device in each interleaf. This system is available at a relatively low cost compared to the counterpulsed devices. In the PF system a counterpulsed thyristor breaker will be connected in series with the explosively actuated device. Due to the absence of moving parts the thyristor breaker is most suitable for maintenance free repetitive operation.

ACKNOWLEDGMENTS

This work was supported by U.S. Department of Energy Contract No. DE-AC02-76CH03073.

REFERENCES

1. C. Neumeyer, et. al., "TPX Power Systems Design Overview", *IEEE/NPSS 15th Symposium on Fusion Engineering*, Hyannis, Massachusetts, October 1993
2. C. Neumeyer, G. Bronner, "Fast Discharge Options for TPX TF & PF SC Magnets", TPX Doc. No. 40-930827-PPPL/CNeumeyer-01

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DATE

FILMED

8 / 9 / 94

END