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WFPS-TME-019
OCTOBER 1975

**Westinghouse Electric Corporation
Fusion Power Systems Department**

TFTR GENERATOR LOAD ASSESSMENT

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ABSTRACT

Typical experimental load demands on the TFTR generators are illustrated based on the electrical characteristics of the field coils, the coil leads, the main bus work, the various auxiliary bus work, the rectifiers, and transformers. The generator MW capacities are shown to be adequate for the proposed experimental operations with allowances made for variations in the final designs. The generator MVA capacities are shown to be adequate provided portions of the TF and EF rectifiers are freewheeled at selected times.

ACKNOWLEDGEMENT

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TABLE OF CONTENTS

<u>Section No.</u>	<u>Title</u>	<u>Page No.</u>
	Abstract	i
1.0	Introduction	1
2.0	Coil Power Supply and Generator Operational Modes	3
3.0	Significant Load Characteristics	8
4.0	Generator Load Systems Details	13
	4.1 Toroidal Field System	13
	4.2 Equilibrium Field System	21
	4.3 Ohmic Heating System	29
	4.4 Neutral Beam System	37
Appendix 1	Relationship Used for Estimating Load Parameters	38
Appendix 2	DC Bus Lengths	43

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page No.</u>
2-1	Load Sequence - No Compression	4
2-2	Load Sequence - Weak Compression	5
2-3	Load Sequence - Strong Compression	6
3-1	MVA Load (No Compression)	12
A-1	Field Coil Power Conversion DC Bus Layout	46

1.0 INTRODUCTION

The electrical systems for TFTR take power from the commercial 138 kV transmission line, transform and distribute it, and store and convert it to meet the Tokamak requirements. The Energy Supply and Distribution System converts the incoming 138 kV power to 13.8 kV and 4.16 kV and distributes the power over the site. This system provides the energy storage by means of motor-generator-flywheel sets which permit averaging the Tokamak pulsed loads over the five minute operating cycle. The pulsed loads supplied by the motor-generator-flywheel sets are:

The Toroidal Field Pulsed Power Conversion System which converts the ac output of the generators into controlled dc at the current level required for the experiment at the TF coils;

The Ohmic Heating Pulsed Power Conversion System which converts the ac output of the generators into controlled dc at the OH coils. It also provides for a high reverse voltage for plasma initiation, rapid current reversal to build the plasma current and temperature, and rapid shutdown for vacuum vessel protection;

The Equilibrium Field Pulsed Power Conversion System which converts the ac output of the generators into controlled dc at the EF coils, and provides the ability to ramp the EF coil current to follow the plasma current buildup and maintain the plasma position. It also provides the capability to provide a large current increase over 20 to 30 milliseconds to compress the plasma;

The power conversion portion of the Neutral Beam System converts the ac output of the generators into controlled dc at several voltage levels for use in generating the neutral beams for injection into the plasma.

The power requirements are basically established by the physics and mechanical parameters. For example, the largest load, the TF coil supply, is essentially fully determined by the required magnetic field, the coil major and minor radii, and the cross section available for copper.

The controlling condition for generator loading as currently defined is the end of the strong compression at $\sim$ IMA. For this case, the total generator loading (two machines) is:

Coincident Peak Loads

	<u>MW</u>	<u>MVA</u>
TF System	380	459*
EF System	264	348
OH System	7	34
NB System	—	—
Total	651	841

* Includes freewheeling of rectifiers, see later discussion.

Thus, two machines of 330 MW/475 MVA have some margin for variations and changes in the experimental scenario and in the analysis.

2.0 COIL POWER SUPPLY AND GENERATOR OPERATIONAL MODES

The power supply (MG sets) and convertor equipment which provide the energy to drive the TF, OH, and EF coils will experience several different operating modes. The equipment design takes into account the fact that these modes are not fixed and immutable but are part of an experimental program. To accomplish this, the power equipment will be thermally sized for slightly more than the reference conditions, and the power conversion equipment will provide the versatility to operate satisfactorily at least down to 10% of the reference conditions of current and voltage.

The principle operating modes are:

- Mode 1 - Plasma Experiment without Compression
- Mode 2 - Plasma Experiment with "Weak" Compression
- Mode 3 - Plasma Experiment with "Strong" Compression

Figures 2-1, 2-2, and 2-3 illustrate power demands typical of the corresponding operating modes. Note that the absolute time and power values are to be considered representative not absolute parameters of a possible set of experimental values.

For each of the Mode 1 cases there will be four distinct phases:

1. Pre-start
2. Start-up
3. Running
4. Shutdown

FIGURE 2-1 LOAD SEQUENCE - NO COMPRESSION

FIGURE 2-2 LOAD SEQUENCE - WEAK COMPRESSION

FIGURE 2-3 LOAD SEQUENCE - STRONG COMPRESSION

The pre-start phase is the interval between plasma experiments. During this phase the generator will be brought up to full speed (~ 90 Hz) and the pulse conversion rectifiers will be blocked by disabling the SCR gate drives.

The start-up phase consists of bringing up the generator field excitation to a value which provides 13.8 kV at the generator buses. Then the TF rectifier will be turned full on to bring up the TF field to the desired level for the next experiment. As the TF approaches full level, the OH rectifier will be turned on to bring up the OH current. The OH rectifier will be operated in a phased back condition to limit the rate of rise of the OH field. This phase draws approximately 80% of the flywheel energy but, with only two of the four main loads drawing power, it does not set the generator rating.

The running phase consists of operation to satisfy the needs of the experiment. This period, lasting up to one second, determines the peak power rating of the generators.

The shutdown phase will consist of ramping the OH and EF currents down rapidly, followed by reversing the TF rectifier voltage to bring the current to zero and recover part of the energy stored in the TF coils. All rectifiers will then be blocked and the generator excitation reduced to minimum.

3.0 SIGNIFICANT LOAD CHARACTERISTICS

The generator loads have been developed on the basis of the best obtainable information as of September 5, 1975.

The various bus and lead lengths should be representative of those actually encountered in the final design. The system time constants are not strongly dependent upon the bus and lead inductances so that variation in bus and lead length will not be significant with respect to inductance (Note: secondary ac buses are an exception to this and these buses must be kept short). The generator loading is dependent upon the bus and lead resistance, but the resistance can be adjusted by changing the copper cross section; therefore, the generator loads can be made relatively insensitive to the bus and lead resistance. The coil resistances and inductances strongly influence the generator loading. These effects cannot be adjusted out by changing the copper cross section and spacing because the cross section and spacing are constrained by the physics and mechanics of the design. Therefore, it is necessary at this stage in the design to allow some margin for the design adjustments in the coils which will occur as the design is finalized. These adjustments will increase the resistance and may increase inductance.

Allowances have, therefore, been made in the pulsed power conversion equipment for the coil and in the generators, for higher than nominal values of resistance and inductance.

These allowances are:

TF - +5% on resistance, +10% on inductance

EF - +10% on resistance, +10% on inductance

OH - +10% on resistance, +10% on inductance

If the coil variations in the final design resulted in the full allowance increase in inductance, the time constants would increase and the response times would suffer. Therefore, each coil

pulsed power convertor provides for increasing the dc voltage by 10% using transformer taps so that the voltage to inductance ratio remains constant.

Table 3-1 is the Summary Generator Load List with the values for the maximum coil resistances and inductances incorporated. The purpose of the non-coincident peak MW column is to serve as a base for estimating the MVA requirements for the systems.

Regardless of the load power, the MVA generator requirements are set by the peak rectifier conditions if the dc current is rated value and no special provisions are made for dealing with the MVA requirements. The MVA does vary essentially linearly with the dc current. It should be noted that on phase controlled thyristor power supplies the peak MW need never occur, yet the MVA drawn by the power supply will vary only with dc current and at full rated current the MVA will have the same value regardless of the dc voltage, i.e., regardless of the MW load.

During the start-up phase, initial buildup to the full TF and OH currents, only the TF and OH loads are on the generators. Therefore, the maximum possible load during this period is 571 MW and 696 MVA. These loads are below rated peak generator capability.

Beyond this period the TF rectifier system requires only the voltage output of approximately three-fourths of the total capability. If one-fourth of the rectifier on each machine is bypassed (free wheeled) then the MVA requirement can be reduced by one-fourth. This will increase the rectifier cost slightly, but will significantly improve the generator voltage by reducing the load current variation during the one second experimental period.

At the beginning of the running phase, during initial plasma current build-up, only the reduced TF and the EF power supplies are on the generator. During this period, while the OH is reversing on the capacitor with the power supply off, the EF is always less than 80% of full current. At 80% full current in the EF, with full EF voltage, the maximum generator output would be 605 MW and 737 MVA. These loads are below rated peak generator capability.

TABLE 3-1
SUMMARY GENERATOR LOAD LIST*

	Non-Coincident		Constant Rated Current		Coincident	
	<u>Peak MW</u>	<u>Peak MVA</u>	<u>MW</u>	<u>MVA</u>	<u>Peak MW</u>	<u>Peak MVA</u>
TF SYSTEM	501	611	380	459**	380	459*
EF SYSTEM	286	348	84	174***	264	348
OH SYSTEM	70	85	45	85	7	34
NB SYSTEM	<u>129</u>	<u>157</u>	<u>129</u>	<u>157</u>	—	—
	986	1201	638	875	651	841

*TF, EF, and Oh coil inductance 10% above nominal TF coil resistance 5%, EF and OH resistance 10% above nominal.

**1/4 of TF rectifier bypassed.

***1/2 of EF rectifier bypassed when NB on.

Near peak load conditions for both MW and MVA occur when the OH, EF, and TF coil loads are combined with the neutral beam injection for the 2.5 MA plasma. During periods when the NB load is on, the TF load is in steady state while the EF current is increasing slightly and the OH current is decreasing slightly. The MVA load goes quite high during this period and would result in excessive voltage swings during the flat top which the generator could not correct because of its inherently long time constant. With no provision for freewheeling the rectifiers, the generator bus voltage for the 2.5 MA plasma, no compression case would swing 12 to 16%, depending on the generator constants. By freewheeling one-fourth of the TF and one-half of the EF over selected portions of the flat top, the voltage swing can be reduced to a value in the range of 5 to 8%. The TF would be freewheeled part way into the flat top to minimize the load dip which otherwise occurs at the beginning, and the EF need be freewheeled only while the NB load is on. The freewheeled TF can deliver full steady state current. The freewheeled EF can deliver up to full rated current with reduced forcing voltage available. During the time the NB are on the full forcing voltage of the EF is not needed and the half voltage output is adequate (only about 27% voltage) to hold 80 kA in the EF. Figure 3-1 illustrated the current leveling of the generator load achievable by freewheeling. For the compression cases the EF current is less than half of full current during the time the NB load is on, drawing less than half the full MVA and therefore need not be freewheeled during this operation.

FIGURE 3-1 MVA LOAD (NO COMPRESSION)

4.0 GENERATOR LOAD SYSTEMS DETAILS

The following material defines the four load systems supplied by the flywheel-generator sets. Half of each system is supplied from each generator.

4.1 TF SYSTEM

Coils

The TF coils alone have a resistance of $.0548\Omega$ (calculated at 20°C and 100% copper conductivity) and an inductance of 0.475 H. Adjusting the resistance value for a maximum temperature of 55°C and 98.4% conductivity yields for nominal value calculations:

Resistance (nom.) $.0548\Omega$ (55°C)

Inductance (nom.) 0.475 H

(Note: Recent calculations yield 0.51H for this value.)

Allowance for uncertainty in the design must be provided. We have arbitrarily selected 5% on the TF resistance and 10% on inductance. The worst case power supply and cooling conditions occur for the high side values. The additional resistance will require margin in MW capacity, in MJ capacity, and in cooling capacity. The additional inductance will be compensated for providing transformer taps to +10% voltage. This will require margin in MVA capacity and, during the field buildup, in MW capacity.

Resistance (max.) 0.0664Ω (55°C)

Inductance (max.) 0.523 H

Coil Jumpers and Leads

The turn-to-turn jumpers make up one turn around the TF coil assembly located at $\sim 265\text{ cm}$. A reverse turn must be provided to cancel the field produced by the jumpers. This will represent approximately $2 \times 55 = 110\text{ ft.}$ of conductor. In addition, leads will be required

out past the edge of the platform to meet the dc bus coming up from the basement. These leads will represent $\sim 2 \times 20 = 40$ ft. of conductor. Because of the limited space available all this conductor is assumed to be similar to the coil conductors, i. e. $\sim 3/4" \times 8"$ with two water cooling channels. This produces:

Resistance 0.00022Ω (55°C)

Inductance $17 \times 10^{-6} \text{ H}$

Main DC Bus Work

The dc bus work has been selected on the basis of the pulse load requirement (~ 11 seconds equivalent square wave out of 300 seconds), and is adequate for continuous operation at $\sim 18\%$ current for vacuum vessel cleaning with 50°C rise in either case. Each side of the bus consists of 6 copper bars $1/4" \times 8"$, assembled in two sets of 3 bars each with a one-inch minimum space between the two sets. This size was selected so that the same size bars in single sets of three can be used for EF and OH to minimize costs.

The electrical characteristics of the TF bus, assuming 470 ft. for each side, are:

Resistance 0.00084Ω (92°C)

Inductance $150 \times 10^{-6} \text{ H}$

The lengths used above are believed to be worst case, therefore, no uncertainty allowance is provided for these values.

Rectifier

For estimating losses, we have assumed a maximum of 16 SCR's in series carrying full current at any time, with 2.0 volts drop across each.

Rectifier Leads and Jumpers

Because the rectifier units are spread out to accommodate the transformers and SCR cooling, the characteristics per foot have been assumed to be a duplicate of the dc buses except for the inductance which is arbitrarily selected as double that of the bus because the spacing cannot be maintained as well as that of the dc bus. An equivalent length of 300 ft. per side is assumed.

Resistance 0.00053Ω (92°C)

Inductance $171 \times 10^{-6} \text{H}$

The above values should be no higher in the final design so no provision need be made for uncertainty.

AC Bus (Secondary Side)

These have been sized for the pulsed load with eight 1000 Mcm conductors per phase. These conductors will be procured as triplex (triple conductor) cable and applied with all three phases in each triplex. This minimizes inductance in this crucial section. Allowing a maximum of 75 ft. of circuit from transformer to rectifier SCR's and providing two secondaries on each of eight transformers gives electrical characteristics:

Resistance $121 \times 10^{-6} \Omega$ (68°C)/phase

Inductance $1.4 \times 10^{-6} \text{H}/\text{phase}$

Transformers

The design has eight three-winding transformers with each of the two secondaries on each transformer carrying one-half the total current. The peak load under nominal conditions is ~ 70 MVA (56 MW) per transformer. With pulse loading the transformers can be overloaded to ~ 2 times their rating, requiring 35 MVA (27 MW) transformers. The transformer impedance can be in the range of 12% to 20% on the 70 MVA base

Transformer losses have been estimated from the T & D Handbook (1950 Edition) as:

Iron Loss $\sim 66\text{kW/transformer}$

Copper Loss $\sim 524\text{ kW/transformer at } 70\text{ MVA}$

AC Bus (Primary Side)

The pulse load on the ac primary side bus can be carried by a single 750 Mcm copper conductor per phase in a single triplex cable for each transformer. In final design it may be more economical to use 1000 Mcm triplex to match the secondary ac conductors but 750 Mcm is adequate and will be used for estimating losses. A total equivalent circuit length of 500 ft. will be used for estimating to include generator and switch-gear circuits. The electrical characteristics are:

Resistance $0.0085\ \Omega/\text{phase}$

Inductance $75 \times 10^{-6}\text{ H/phase}$

Summary of TF System

The system parameters are summarized in Tables 4.1-1 and 4.1-2 for the nominal and maximum case values respectively. Note that the voltage available is 10% higher for the maximum case to compensate for the higher inductance. The loads created by each portion of the system at rated current are summarized in Tables 4.1-3 and 4.1-4 for nominal and maximum case conditions.

TABLE 4.1-1
TF SYSTEM PARAMETERS - NOMINAL VALUES

DC Resistance:	
Coils	0.0632 Ω
Other	<u>0.00155 Ω</u>
Total	0.06475 Ω
DC Voltage	6.0 kV
AC Losses (at 73.2 kA dc):	
Rectifier	2.3 MW
Secondary ac Bus	5.2 MW
Transformer	4.7 MW
Primary ac Bus	<u>1.8 MW</u>
Total	14.0 MW
DC Inductance:	
Coils	0.475 H
Other	<u>0.00034 H</u>
Total	0.47534 H
AC Inductance:	
Secondary ac Bus	1.3×10^{-6} H/ph
Transformer (15% on 70 MVA at 13.8 kV)	0.0011 H/ph
Primary ac Bus	75×10^{-6} H/ph
Generator (35% on 475 MVA at 13.8 kV)	372×10^{-6} H/ph

TABLE 4.1-2
TF SYSTEM PARAMETERS - MAXIMUM VALUES

DC Resistance:

Coils	0.0664 Ω
Other	<u>0.00155 Ω</u>
Total	0.06795 Ω

DC Voltage

6.6 kV

AC Losses (at 73.2 kA dc):

Rectifier	2.3 MW
Secondary ac Bus	5.2 MW
Transformer	5.6 MW
Primary ac Bus	<u>2.1 MW</u>
Total	15.2 MW

DC Inductance:

Coils	0.523 H
Other	<u>0.00034 H</u>
Total	0.52334 H

AC Inductance:

Secondary ac Bus	1.3×10^{-6} H/ph
Transformer (15% on 70 MVA at 13.8 kV)	0.0011 H/ph
Primary ac Bus	75×10^{-6} H/ph
Generator (35% on 475 MVA at 13.8 kV)	372×10^{-6} H/ph

TABLE 4.1-4
TF SYSTEM LOAD - MAXIMUM VALUES
73.2 kA Peak Current

<u>ITEM</u>	<u>PEAK MW</u>	<u>FLAT TOP MW</u>	<u>MVA</u>
Coils: Induction	121.6	0	
I^2R	355.8	355.8	
Coil Leads, Jumpers	1.2	1.2	
DC Bus	4.5	4.5	
Rectifier	2.3	2.3	
Rectifier Leads, Jumpers	2.8	2.8	
AC Bus (Secondary Side)	5.2	5.2	
Transformers: Fe	0.5	0.5	
Cu	5.1	5.1	
AC Bus (Primary Side)	2.1	2.1	
Total Losses (excluding coils)	23.5	23.5	
Total Load	500.9	379.3	611/458

TABLE 4.1-3
TF SYSTEM LOAD - NOMINAL VALUES
73.2 kA Peak Current

<u>ITEM</u>	<u>PEAK MW</u>	<u>FLAT TOP MW</u>	<u>MVA</u>
Coils: Induction:	94.9	0	
I^2R	338.6	338.6	
Coil Leads, Jumpers	1.2	1.2	
DC Bus	4.5	4.5	
Rectifier	2.3	2.3	
Rectifier Leads, Jumpers	2.8	2.8	
AC Bus (Secondary Side)	5.2	5.2	
Transformers: Fe	0.5	0.5	
Cu	4.2	4.2	
AC Bus (Primary Side)	1.8	1.8	
Total Losses (excluding coils)	22.5	22.5	
Total Load	456.0	361.1	556/417

4.2 EF SYSTEM

Coils

The EF coils alone have a resistance of 0.00642Ω (calculated at 20°C and 100% copper conductivity and an inductance of $.00623$. Adjusting the resistance values for a maximum temperature of 55°C and 98.4% conductivity yields for nominal value calculations:

Resistance (nom.) 0.00735Ω

Inductance (nom.) 0.00623 H

Allowance for uncertainty in the design must be provided. We have arbitrarily selected 10% on both resistance and inductance of the EF coils. The worst case power supply and cooling conditions occur for the high side values. The additional resistance will require margin in MW capacity, in MJ capacity, and in cooling capacity. The additional inductance will be compensated for by providing transformer taps to + 10% voltage. This will require margin in MVA capacity and, during field buildup, in MW capacity.

Resistance (max.) 0.00808Ω

Inductance (max.) 0.00685 H

Coil Jumpers and Leads

The turn-to-turn jumpers make up nearly one turn around the vacuum vessel on a radius of approximately 240 cm from the torus center line. A reverse turn must be provided to cancel the field produced by the jumpers. This will represent approximately $2 \times 50 = 100$ ft. of conductor. In addition, leads will be required out past the edge of the platform to meet the dc bus coming up from the basement. These leads will represent $\sim 2 \times 27.5 = 55$ ft. of conductor. Because of the limited space available all this conductor is assumed to be similar to the coil conductors, i. e., $\sim 1 \frac{1}{2}'' \times 1 \frac{1}{2}''$ with a water cooling channel. This results in:

Resistance 0.00034Ω (55°C)

Inductance $23 \times 10^{-6} \text{ H}$

Main DC Bus Work

The dc buswork has been selected on the basis of the pulse load requirement (~ 4 seconds equivalent square wave out of 300 seconds), and is adequate for reduced pulse operation at shorter intervals. Each side of the bus consists of 3 copper bars $1/4" \times 8"$. This size was selected so that the same size bars could be used in TF, OH, and EF.

The electrical characteristics of the OH bus, assuming 370 ft. each side are:

Resistance 0.00131Ω

Inductance $121 \times 10^{-6} \text{ H}$

The length above is believed to be the worst case value, hence no uncertainty allowance is provided for these values.

Capacitor DC Bus Work

The bus out to the capacitor bank and back to the switching center will be identical with the main dc bus except that it will be 310 ft. The electrical characteristics of this bus are:

Resistance 0.00110Ω

Inductance $102 \times 10^{-6} \text{ H}$

No uncertainty allowance is provided for these values.

Rectifier

For estimating losses, we have assumed a maximum of 8 SCR's in series carrying full current at any time, with 2.0 volts drop across each.

Rectifier Leads and Jumpers

Because the rectifier units are spread out to accommodate the transformers and SCR cooling, the characteristics per foot have been assumed to be a duplicate of the dc bus except for the inductance which is arbitrarily selected as double that of the bus because the spacing cannot be maintained as well as that of the dc bus. An equivalent length of the 300 ft. is assumed.

Resistance 0.00107Ω

Inductance $157 \times 10^{-6} \text{ H}$

The above values should be no higher in the final design so no provision need be made for uncertainty.

AC Bus (Secondary Side)

These have been sized for the pulsed load with 6-1000 Mcm conductors per phase. These conductors will be procured as triplex cable and applied with all three phases in each triplex to minimize inductance in this critical area. Allowing a maximum of 75 ft. of circuit and providing two secondaries on each of two transformers gives as electrical characteristics:

Resistance $0.00016 \Omega (68^\circ \text{C})$ per phase

Inductance $1.8 \times 10^{-6} \text{ H}$ per phase

Transformers

The design has four three-winding transformers with each of the two secondaries on each transformer carrying one-half the total current. The peak load under nominal conditions is $\sim 64 \text{ MVA}$ (51 MW) per transformer. With pulse loading the transformers can be overloaded to ~ 2 times their rating, requiring 30 MVA (26 MW) per transformer. The transformer impedance can be in the 12% to 20% on the 64 MVA base.

Transformer losses have been estimated from the T & D Handbook (1950 Edition) as:

Iron Loss ~ 60 kW/transformer

Copper Loss ~ 563 kW/transformer

AC Bus (Primary Side)

The pulse load on the ac primary side bus can be carried by a single number 1/0 copper conductor per phase in a single triplex cable for each transformer. A total equivalent circuit length of 500 ft. will be used for estimating to include generator and switchgear circuits. The electrical characteristics are:

Resistance 0.06102Ω /phase

Inductance 106×10^{-6} H/phase

Summary of EF System

The system parameters are summarized in Tables 4.2-1 and 4.2-2 for the nominal and maximum cases respectively. Note that the voltage available is 10% higher for the maximum case to compensate for the higher inductance. The loads created by each portion of the system at rated current are summarized in Tables 4.2-3 and 4.2-4 for the nominal and maximum case conditions.

TABLE 4.2-1
EF SYSTEM PARAMETERS - NOMINAL VALUES

DC Resistance:	
Coils	0.00735 Ω
Other	<u>0.00272 Ω</u>
Total	0.01007 Ω
DC Voltage	3.0 kV
AC Losses (at 40 kA DC):	
Rectifier	1.3 MW
Secondary ac Bus	4.1 MW
Transformer	2.5 MW
Primary ac Bus	<u>5.0 MW</u>
Total	12.9 MW
DC Inductance:	
Coils	0.00623 H
Other	<u>0.00030 H</u>
Total	0.00653 H
AC Inductance:	
Secondary ac Bus	1.8×10^{-6} H/ph
Transformer (15% on 64 MVA at 13.8 kV)	0.00118 H/ph
Primary ac Bus	106×10^{-6} H/ph
Generator (35% on 475 MVA at 13.8 kV)	372×10^{-6} H/ph
Capacitor dc Bus:	
Resistance	0.00110 Ω
Inductance	121×10^{-6} H

TABLE 4.2-2
EF SYSTEM PARAMETERS - MAXIMUM VALUES

DC Resistance:

Coils	0.00808 Ω
Other	<u>0.00272 Ω</u>
Total	0.01080 Ω

DC Voltage

3.3 kV

AC Losses (at 80 kA dc):

Rectifiers	1.3 MW
Secondary ac Bus	4.1 MW
Transformer	2.9 MW
Primary ac Bus	<u>6.0 MW</u>
Total	14.3 MW

DC Inductance:

Coils	0.00685 H
Other	<u>0.00030 H</u>
Total	0.00715 H

AC Inductance:

Secondary ac Bus	1.8×10^{-6} H/ph
Transformer (15% on 64 MVA at 13.8 kV)	0.00118 H/ph
Primary ac Bus	106×10^{-6} H/ph
Generator (35% on 475 MVA at 13.8 kV)	372×10^{-6} H/ph

Capacitor dc Bus:

Resistance	0.00110 Ω
Inductance	121×10^{-6} H

TABLE 4.2-3

EF SYSTEM LOAD - NOMINAL VALUES

80 kA Peak Current

<u>ITEM</u>	<u>PEAK MW</u>	<u>FLAT TOP MW</u>	<u>MVA</u>
Coils: Induction	182.4	0	
I^2R	47.0	47.0	
Coil Leads, Jumpers	2.2	2.2	
DC Bus	8.4	8.4	
Rectifier	1.3	1.3	
Rectifier Leads, Jumpers	6.8	6.8	
AC Bus (Secondary Side)	4.1	4.1	
Transformers: Fe	0.2	0.2	
Cu	2.3	2.3	
AC Bus (Primary Side)	5.0	5.0	
Total Losses (excluding coils)	30.3	30.3	
Total Load	259.7	77.3	316

TABLE 4.2-4

EF SYSTEM LOAD - MAXIMUM VALUES

80 kA Peak Current

<u>ITEM</u>	<u>PEAK MW</u>	<u>FLAT TOP MW</u>	<u>MVA</u>
Coils: Induction	201.7	0	
I^2R	51.7	51.7	
Coil Leads, Jumpers	2.2	2.2	
DC Bus	8.4	8.4	
Rectifier	1.3	1.3	
Rectifier Leads, Jumpers	6.8	6.8	
AC Bus (Secondary Side)	4.1	4.1	
Transformers: Fe	0.2	0.2	
Cu	2.7	0.7	
AC Bus (Primary Side)	6.0	6.0	
Total Losses (excluding coils)	31.7	31.7	
Total Load	285.1	83.4	348

C. OH SYSTEM

Coils

The OH coils alone have a resistance of 0.01779Ω (calculated at 20°C and 100% copper conductivity) and an inductance of 0.02701H . Adjusting the resistance values for a maximum temperature of 55°C and 98.4% conductivity yields for nominal value calculations:

Resistance (nom.) $0.02066\ \Omega$

Inductance (nom.) $0.02701\ \text{H}$

Allowance for uncertainty in the design must be provided. We have arbitrarily selected 10% on both resistance and inductance of the OH coils. The worst case power supply and cooling conditions occur for the high side values. The additional resistance will require margin in MW capacity, in MJ capacity, and in cooling capacity. The additional inductance will be compensated for by providing transformer taps to +10% voltage. This will require margin in MVA capacity and, during field buildup, in MW capacity.

Resistance (max.) $0.02273\ \Omega$

Inductance (max.) $0.02971\ \text{H}$

Coil Jumpers and Leads

The turn-to-turn jumpers make up nearly one turn around the vacuum vessel on a radius of approximately 240 cm from the torus center line. A reverse turn must be provided to cancel the field produced by the jumpers. This will represent approximately $2 \times 50 = 100\ \text{ft.}$ of conductor. In addition, leads will be required out past the edge of the platform to meet the dc bus coming up from the basement. These leads will represent $\sim 2 \times 27.5 = 55\ \text{ft.}$ of conductor. Because of the limited space available all this conductor is assumed to be similar to the coil conductors, i. e., $\sim 1\ 1/2" \times 1\ 1/2"$ with a water cooling channel. This results in:

Resistance $0.00073\ \Omega$ (55°C)

Inductance $27 \times 10^{-6}\ \text{H}$

Main DC Bus Work

The dc bus work has been selected on the basis of the pulse load requirement (~ 4 seconds equivalent square wave out of 300 seconds), and is adequate for reduced pulse operation at shorter intervals. Each side of the bus consists of 3 copper bars $1/4" \times 8"$. This size was selected so that the same size bars could be used in the TF, OH, and EF.

The electrical characteristics of the OH bus, assuming 490 ft. each side, are:

Resistance 0.00175Ω

Inductance $161 \times 10^{-6} \text{ H}$

The length above is believed to be the worst case value, hence no uncertainty allowance is provided for these values.

Capacitor DC Bus Work

The bus out to the capacitor bank and back to the switching center will be identical with the main dc bus except that it will be 310 ft. The electrical characteristics of this bus are:

Resistance 0.00111Ω

Inductance $94 \times 10^{-6} \text{ H}$

No uncertainty allowance is provided for these values.

Rectifier

For estimating losses, we have assumed a maximum of 4 SCR's in series carrying full current at any time, with 2.0 volts drop across each.

Rectifier Leads and Jumpers

Because the rectifier units are spread out to accommodate the transformers and SCR cooling, the characteristics per foot have been assumed to be a duplicate of the dc bus except for the inductance which is arbitrarily selected as double that of the bus because the spacing cannot be maintained as well as that of the dc bus. An equivalent length of 250 ft. is assumed.

Resistance 0.00089Ω

Inductance $159 \times 10^{-6} \text{ H}$

The above values should be no higher in the final design so no provision need be made for uncertainty.

AC Bus (Secondary Side)

These have been sized for the pulsed load with 6-1000 Mcm conductors per phase. These conductors will be procured as triplex cable and applied with all three phases in each triplex to minimize inductance in this critical area. Allowing a maximum of 75 ft. of circuit and providing two secondaries on each of two transformers gives as electrical characteristics:

Resistance 0.00016Ω (68°C) per phase

Inductance $1.8 \times 10^{-6} \text{ H}$ per phase

Transformers

The design has two three-winding transformers with each of the two secondaries on each transformer carrying one-half the total current. The peak load under nominal conditions is $\sim 32 \text{ MVA}$ (26 MW) per transformer. With pulse loading the transformers can be overloaded to ~ 2 times their rating, requiring 16 MVA (13 MW) per transformer. The transformer impedance can be in the 12% to 20% on the 32 MVA base.

Transformer losses have been estimated from the T & D Handbook (1950 Edition) as:

Iron Loss ~ 39 kW/transformer

Copper Loss ~ 333 kW/transformer

AC Bus (Primary Side)

The pulse load on the ac primary side bus can be carried by a single number 2 copper conductor per phase in a single triplex cable for each transformer. A total equivalent circuit length of 500 feet will be used for estimating to include generator and switch-gear circuits. The electrical characteristics are:

Resistance 0.9680Ω /phase

Inductance 100×10^{-6} H/phase

Summary of OH System

The system parameters are summarized in Tables 4.3-1 and 4.3-2 for the nominal and maximum case values respectively. Note that the voltage available is 10% higher for the maximum case to compensate for the higher inductance. The loads created by each portion of the system at rated current are summarized in Tables 4.3-3 and 4.3-4 for nominal and maximum case conditions.

TABLE 4.3-1
OH SYSTEM PARAMETERS - NOMINAL VALUES

DC Resistance:		
Coils		0.02066 Ω
Other		<u>0.00337 Ω</u>
Total		0.02403 Ω
DC Voltage		1.5 kV
AC Losses (at 40 kA dc):		
Rectifier		0.3 MW
Secondary ac Bus		0.5 MW
Transformer		0.8 MW
Primary ac Bus		<u>1.0 MW</u>
Total		2.6 MW
DC Inductance:		
Coils		0.02701 H
Other		<u>0.00039 H</u>
Total		0.02740 H
AC Inductance:		
Secondary ac Bus		1.8×10^{-6} H/ph
Transformer (15% on 32 MVA at 13.8 kV)		0.00237 H/ph
Primary ac Bus		100×10^{-6} H/ph
Generator (35% on 475 MVA at 13.8 kV)		372×10^{-6} H/ph
Capacitor DC Bus:		
Resistance		0.00111 Ω
Inductance		94×10^{-6} H

TABLE 4.3-2
OH SYSTEM PARAMETERS - MAXIMUM VALUES

DC Resistance:	
Coils	0.02273 Ω
Other	<u>0.00337 Ω</u>
Total	0.02610 Ω
DC Voltage	1.65 kV
AC Losses (at 40 kA dc):	
Rectifier	0.3 MW
Secondary ac Bus	0.5 MW
Transformer	0.9 MW
Primary ac Bus	<u>1.2 MW</u>
Total	2.9 MW
DC Inductance:	
Coils	0.02971 H
Other	<u>0.00039 H</u>
Total	0.03010 H
AC Inductance:	
Secondary ac Bus	1.8×10^{-6} H/ph
Transformer	0.00237 H/ph
Primary ac Bus	100×10^{-6} H/ph
Generator (35% on 475 MVA at 13.8 kV)	372×10^{-6} H/ph
Capacitor DC Bus:	
Resistance	0.00111 Ω
Inductance	94×10^{-6} H

TABLE 4.3-3
OH SYSTEM LOAD - NOMINAL VALUES
40 kA Peak Current

<u>ITEM</u>	<u>PEAK MW</u>	<u>FLAT TOP MW</u>	<u>MVA</u>
Coils: Induction	22.9		
I^2R	33.1	33.1	
Coil Leads, Jumpers	1.2	1.2	
DC Bus	2.8	2.8	
Rectifier	0.3	0.3	
Rectifier Leads, Jumpers	1.4	1.4	
AC Bus (Secondary Side)	0.5	0.5	
Transformers: FE	0.1	0.1	
Cu	0.7	0.7	
AC Bus (Primary Side)	1.0	1.0	
Total losses (excluding coils)	8.0	8.0	
Total Load	64.0	41.1	78

TABLE 4.3-4
OH SYSTEM LOAD - MAXIMUM VALUES
40 kA Peak Current

<u>ITEM</u>	<u>PEAK MW</u>	<u>FLAT TOP MW</u>	<u>MVA</u>
Coils: Induction	25.6	0	
I^2R	36.4	36.4	
Coil Leads, Jumpers	1.2	1.2	
DC Bus	2.8	2.8	
Rectifier	0.3	0.3	
Rectifier Leads, Jumpers	1.4	1.4	
AC Bus (Secondary Side)	0.5	0.5	
Transformers: Fe	0.1	0.1	
Cu	0.8	0.8	
AC Bus (Primary Side)	1.2	1.2	
Total Losses (excluding coils)	8.3	8.3	86
Total Load	70.3	44.7	

4.4 NEUTRAL BEAM SYSTEM

The September, 1975 ORNL report on the TFTR NB design defines the load at the input to the local switchgear as 10.3 MW per ion source, or a total of 123.6 MW. This provides a total of 80 MW to the NB sources. This results in a current of approximately 3 kA per phase from each generator. With an on-time of one-half to one second, this can be carried by No. 1/0 conductors 750 feet from each generator. This produces a peak line loss of 5.1 MW, making the total generator load 128.7 MW. The sources receive 80 MW of this, so the total system losses are 48.7 MW.

APPENDIX 1

RELATIONSHIP USED FOR ESTIMATING LOAD PARAMETERS

1. Current Buildup in Simple Circuit (Constant Voltage)

In a simple circuit consisting of a voltage source of magnitude V , a resistance R , and an inductance L , the current is defined from:

$$V = IR + L \frac{di}{dt}$$

The characteristic time constant is:

$$\tau = L/R$$

If the voltage is applied at its full value, V_m , and left constant until the current reaches some rated value, I_m ($< V/R$) then:

$$I = V_m (1 - e^{-t/\tau}) / R,$$

the time to reach I_m is

$$T = \tau \ln \left(1 - \frac{I_m R}{V_m} \right),$$

and the voltage required to reach I_m in time, T , is

$$V_R = I_m R / (1 - e^{-T/\tau})$$

The total energy delivered by the voltage source from time zero to time T is:

$$J_T = (V_m^2 T/R) - V_m \tau I_m'$$

and the equivalent square wave time at full I_m is

$$S = \left((V_m^2 T/R) - V_m \tau I_m' \right) / I_m^2 R - \tau/2 \text{ for } 0 \text{ to } T.$$

The initial rate of current rise is

$$\frac{dI}{dt} = V_m/R,$$

and the rate of current rise as I_m is just reached is

$$\frac{dI}{dt}_{t=T} = (V_m - I_m R)/L$$

Total peak power input occurs as I_m is just reached and is

$$P = V_m I_m'$$

and the power just after I_m is reached is

$$P = I_m^2 R$$

II. Secondary AC Bus Losses

The peak current per ac phase feeding a 3 Φ rectifier is just the peak dc current, I_m' , divided by the number of parallel dc rectifier modules, p , used to provide the current. Then the peak power loss in the entire set of secondary busses is:

$$L_b = \left(\frac{I_m}{p} \right)^2 R_b 3T = I_m^2 3T R_b / p$$

where R_b is AC bus resistance per phase,

T = number of series modules used to obtain the voltage

Note that if the amperes per unit area is maintained the same, then the ratio of R_b/p is a constant and the losses do not depend upon the number of units in parallel.

III. Rectifier Losses

The losses in the rectifiers can be approximated from a typical 2.0 volt drop across each rectifier element. Hence if there are N rectifier elements required in series to withstand the peak inverse voltage then the loss for the total assembly is

$$L_r = 2.0 N I_m$$

Note that N is the product of the number of rectifier elements required to withstand the peak inverse voltage per series rectifier module times the number of modules in series.

IV. Transformer Losses

The transformer peak load is the sum of the peak dc power delivered plus the losses in secondary ac buses L_b and rectifier losses, L_r .

$$L_f = \frac{V_m I_m}{T \times p. f.} + L_b + L_r, \quad T = \text{number of transformers.}$$

The transformer rating L_R may be significantly different from the peak level, L_f .

For short pulse loadings the value of L_R may be set from the allowable inductance in the circuit. The inductance of a transformer is variable by design over only a small range for a given MVA transformer rating. The inductance essentially varies inversely with the rated MVA of the transformer. A factor of two between L_t and L_R , i. e., $L_R = L_t/2$ is a good compromise value for the TF, EF, and OH circuits.

Transformer losses are frequently stated in terms of two factors, the C_u and F_e loss product and ratio. The product and ratio values are respectively the product, p and ratio, r , of the C_u and F_e losses when they are expressed as percentages of the full load at the rated MVA of the transformer.

Then the absolute losses per transformer at full rated power are:

$$L_F = \frac{L_R}{100} \sqrt{\frac{p}{r}}$$

$$L_C = \frac{L_R}{100} \sqrt{pr}$$

The copper loss at the actual load is:

$$\left(\frac{L}{L_R}\right)^2 L_C = \frac{L^2}{100 L_R} \sqrt{pr}$$

The total full power loss per transformer is:

$$\frac{L_R}{100} \sqrt{\frac{p}{r}} + \frac{L^2}{100 L_R} \sqrt{pr}$$

The value used for r was 2, 0 for all cases. The values used for p were 0. 07 for TF, 0. 09 for EF, and 0. 12 for OH.

V. Primary AC Bus Losses

Assuming a separate line or bus is feeding each transformer, the peak load on each ac bus is the same as the peak transformer load,

$$L = \frac{V_m I_m}{T \times \text{p. f.}} + L_b + L_r$$

then the peak phase current is:

$$\frac{L}{13.8 \sqrt{3}}$$

and the total loss is:

$$L_{b2} = 3 \left(\frac{L}{13.8 \sqrt{3}} \right)^2 R_{b2} T, \quad T = \text{number of transformers;}$$

$R_{b2} = \text{bus resistance per phase}$

$$L_{b2} = \left(\frac{L}{13.8} \right)^2 R_{b2} T$$

APPENDIX 2
DC BUS LENGTHS

TF BUS LENGTHS

Main Bus

Riser in Cell	20 ft.
Cell to Conversion Building	295 ft.
Riser in Conversion Building	35 ft.
Run in Conversion Building	115 ft.
Riser at Converter	<u>5 ft.</u>
	470 ft.

Rectifier Leads & Jumpers

Riser for Each Module	80 ft.
Run in Each Module	80 ft.
Jumpers	<u>140 ft.</u>
	300 ft.

EF BUS LENGTHS

Main Bus

Riser in Cell	20 ft.
Cell to Conversion Building	325 ft.
Riser in Conversion Building	<u>25 ft.</u>
	370 ft.

Rectifier Leads & Jumpers

Riser for Each Module	40 ft.
Run in Each Module	40 ft.
Jumpers	40 ft.
Rectifier to Switches	50 ft.
Risers at Switches	30 ft.
Leads at Switches	<u>100 ft.</u>
	300 ft.

Capacitor Leads

Leads from Switches	50 ft.
Riser from Tunnel to Switches	20 ft.
Tunnel Run	50 ft.
Riser from Tunnel to Yard	35 ft.
Yard Run	60 ft.
Riser from Cap.	15 ft.
Capacitor Run	<u>80 ft.</u>
	310 ft.

OH BUS LENGTHS

Main Bus

Riser in Cell	20 ft.
Cell to Conversion Building	435 ft.
Riser in Conversion Building	<u>35 ft.</u>
	490 ft.

Rectifier Leads & Jumpers

Riser for Each Module	20 ft.
Run in Each Module	20 ft.
Rectifier to Switches	40 ft.
Risers at Switches	30 ft.
Leads at Switches	<u>140 ft.</u>
	250 ft.

Capacitor Leads

Leads from Switches	50 ft.
Riser from Tunnel to Switches	20 ft.
Tunnel Run	50 ft.
Riser from Tunnel to Yard	35 ft.
Yard Run	60 ft.
Riser from Capacitor	15 ft.
Capacitor Run	<u>80 ft.</u>
	310 ft.

The lengths are estimated on Figure A-1.

TFTQ
BUILDING
COMPLEX

EARTH SHIELD

TUNNEL

4160/440
YARD

EF CAP
YARD
65' x 65'

100' x 165'

EF
SW

BO

CONTROL
C

OH
SW

OH CAP
YARD
65' x 65'

TRANS-
FORMER

MG BLDG

Figure A-1. Field Coil Power Conversion DC Bus Layout