Conf-9504138--1

GA–A21957

DIII–D POWER SUPPLY, DESIGN, AND DEVELOPMENT

by

A. NEREM

FEBRUARY 1995

GENERAL ATOMICS

DISCLAIMER

DISCLAIMER

GA–A21957

DIII–D POWER SUPPLY, DESIGN, AND DEVELOPMENT

by

A. NEREM

This is a preprint of an paper to be presented at the International Power Electronics Conference, April 3–7,1995, in Yokohama, Japan, and to be printed in the *PROCEEDINGS*.

Work supported by
the U.S. Department of Energy
under Contract No. DE-AC03-89ER51114

GA PROJECT 3466
FEBRUARY 1995

TJ

GENERAL ATOMICS

DIII–D Power Supply, Design and Development

A. Nerem

General Atomics, P.O. Box 85608, San Diego, California 92186–9784

Abstract. An overview of the DIII–D power supply system with information details concerning the configuration, power ratings, acquisition costs, and cost scaling relevant to the design of ITER and other tokamaks is presented. The power supplies for the DIII–D tokamak were installed and commissioned during the late 1970's and the beginning of the 1980's. Several upgrades have been implemented during the last two years to solve increasing reliability problems encountered as the equipment aged, to provide enhanced operational flexibilities, and to enable operation at the higher power levels needed to provide experimental data relevant to the ITER and TPX design activities. These upgrades ranged from redesign of the power supply control systems to the replacement of vacuum circuit breakers which had become unreliable in service. A new interlock and protection system has also been implemented using the latest programmable logic controllers (PLC) and computer technology. These upgrades have been highly successful and are described to provide insight to many issues in the specification of high power converters. Power supply models used in the design of the DIII–D Plasma Control System are also described along with model verification test data. These models are being used in the development of a new advanced plasma control system for the DIII–D tokamak. Recent operational experience and results are presented.

Overview of the DIII–D Power Supply System

Facility Power

The DIII–D facility has ~115 MVA of installed utility power service. This power is supplied via substations from 138 kV, 69 kV, and 4.16 kV power transmission lines. In addition, two large motor generators provide a combined extractable stored energy source of 3 GJ. These energy sources are used to power the tokamak coil and auxiliary heating systems used in the tokamak plasma operations. The total annual electric power consumption for DIII–D is ~14 GWhrs. Figure 1 shows a simplified diagram of the DIII–D tokamak electrical systems. This diagram shows that the 69 kV substation is the power source for the tokamak coil power systems. This substation also supplies power to all the tokamak support systems and generally for the DIII–D facility. The 138 kV substation is the power source for the tokamak auxiliary heating systems. A "tie-line" between the two substation output busses is used for occasional testing of the coil power systems at reduced power.

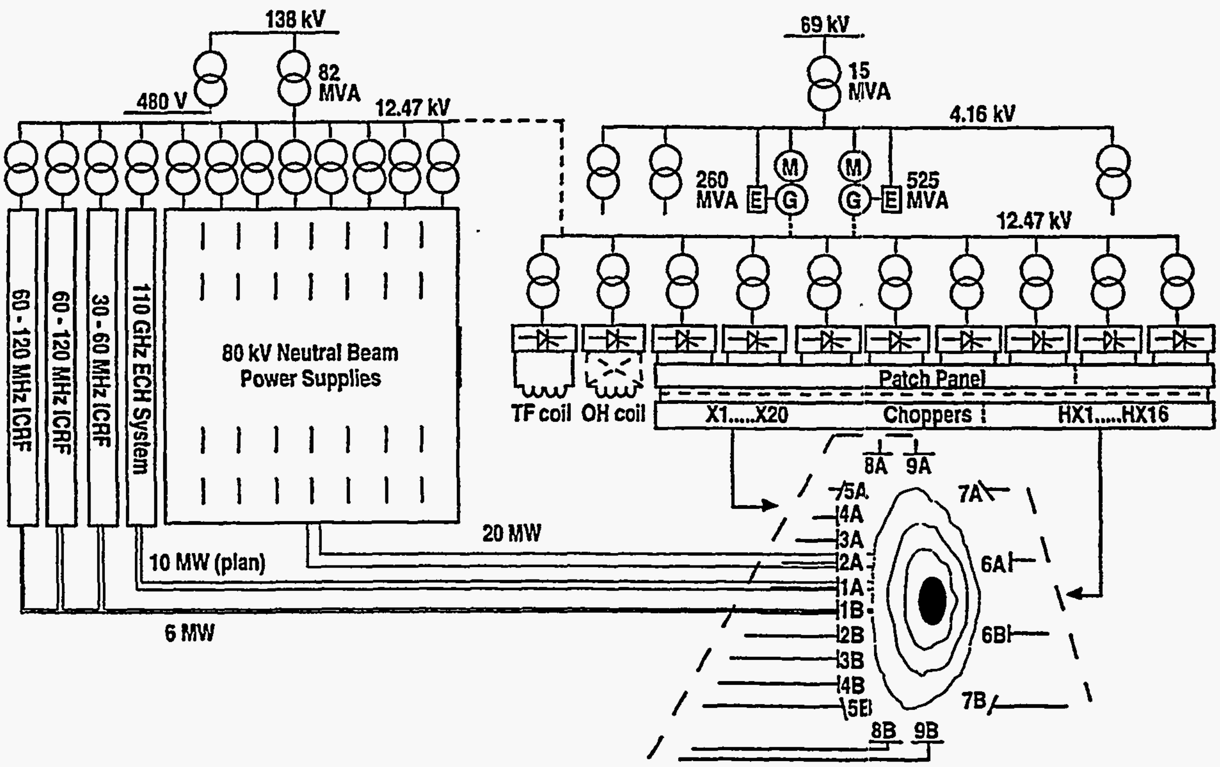

Fig. 1. DIII–D Electrical Systems

Coil Power System

The DIII-D ohmic heating (OH) and toroidal field (TF) coils, are powered by line-commutated SCR phase control rectifier power supplies with a combined power rating of 500 MVA. Together, these two coils provide the magnetic confinement and ohmic current drive fields for the tokamak. High current switches are used to switch the polarity of the OH power supply during plasma shots. These switches have been relatively trouble free when maintained according to our regular schedule. Eighteen additional poloidal field (PF) coils on this tokamak are used to control the shape and position of the plasma current during discharges. These coils are powered from dc/dc converters (choppers) which in turn are powered from additional phase control rectifier power supplies. A patch panel provides flexibility for changing the configuration of the poloidal field coil electrical circuit to accommodate various experimental needs. Altogether, there are 36 choppers and seven power supplies in the DIII-D PF coil power system. Eighteen of these (HX) choppers are rated 1200 V and 3 kA. The other 18 (X) choppers are rated 600 V and 3 kA. The respective high (1200 V) and low (600 V) voltage power supplies for the choppers are nominally rated 20 kA. Typical coil currents during a plasma shot are shown in Fig. 2.

Auxiliary Heating Power Systems

The DIII-D auxiliary heating and current drive systems consist of eight 80 kV 3 MW neutral beam power sources, three 2 MW rf (30–120 MHz) sources, and one 0.5 MW 110 GHz electron cyclotron heating (ECH) rf source. Combined, the eight neutral beam sources inject up to 20 MW of neutral deuterium particles into the plasma. The three rf sources provide up to 6 MW of ion cyclotron heating and fast wave current drive power, and the 0.5 MW 110 GHz ECH system is planned to be expanded to 10 MW. Because of the high frequency and power level requirements from the rf sources, a significant development and test program had to be implemented at GA's site in cooperation with the equipment manufacturers. GA has designed and fabricated major portions of the ECH systems and their transmission line components, and provides similar components and services to other laboratories.

Power Supply Cost Data

Power supply cost data is needed for the planning of new fusion research facilities such as ITER and TPX. The existing fusion research facilities are sources of cost data for power supply equipment of a wide range of topologies and power ratings. While these data are not current, they can be useful when adjusted to reflect current market pricing.

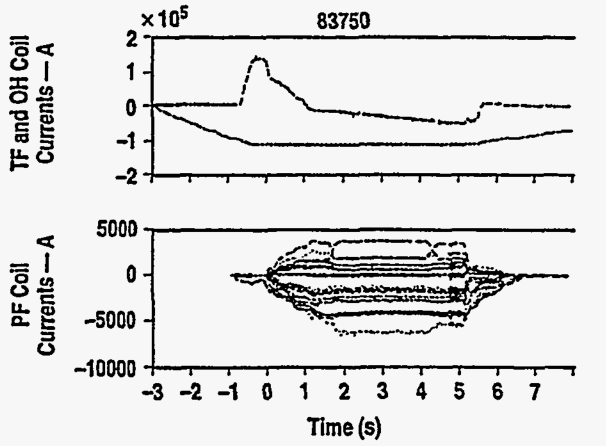

Fig. 2. Typical Coil Currents in DIII-D

DIII-D Power Supply Cost

The acquisition cost for the major DIII-D power supplies are shown in Table 1 along with power supply ratings and the year of purchase. The cost data for the SCR power converters and the motor generators are also plotted in Fig. 3. U.S. Consumer Index cost escalation data was used to project the costs of the SCR phase control rectifier power supplies and the motor generators over the period from 1975 to 1995 to produce the cost trends shown in the figure. Power supply costs from Table 1 are shown as data points in this figure, and the variation in the U.S. Consumer Price Index was used to calculate the curves through each of these data points. It appears from the resulting graph that the U.S. Consumer Price Index is a reasonable indicator of cost trends for the DIII-D power supply equipment. A recent (1994) conceptual cost estimate[1,2] which was prepared for an ITER coil power converter was also included in the cost data. A somewhat surprising observation is that the cost of the two motor generators appear to follow the same general scaling and cost trends as the SCR power supplies for the DIII-D electrical systems.

Upgrades to the DIII-D Power Supply System

Motivation for the Upgrades

The motivation to upgrade the DIII-D power supply equipment comes from the need to meet the demands of new higher power operation regimes, and the need to reduce the downtime attributable to equipment malfunctions. Additional motivation comes from the need for greater flexibility in operating more systems and piggyback experiments. The

Table 1 — DIII-D Power Supply Cost Data

Application	Output (Volts)	Output (kA)	Output (MVA)	Year	Acquisition Cost (K$)
Motor Generator — MG1	13,800	10.9	260	1975	2,512
Motor Generator — MG2 (installed)	13,800	22	525	1981	7,434
Ohmic Heating Power Supply	600	300	290	1976	1,452
Toroidal Field Power Supply	1,000	127	208	1976	1,452
Field Coil Power Supply — D,V	520	24	19	1977	260
Field Coil Power Supply — D2	600	14	12.6	1984	250
Field Coil Power Supply — HV1	1,200	20	32	1981	312
Field Coil Power Supply — HV2	1,200	20	32	1984	312
Field Coil Power Supply — T	600	6	4.8	1982	94
X Choppers (20)	480	3	1.4	1979	1,600
HX Choppers (16)	960	3	2.9	1979	1,280
NB Power Supplies 1,2,3,4	80,000	0.1	8	1980	8,410
NB Power Supplies 5,6,7,8	80,000	0.1	8	1982	7,734
ICRF Transmitter 30–60 MHz			2	1986	1,110
ICRF Transmitter 60–120 MHz			4	1994	3,768

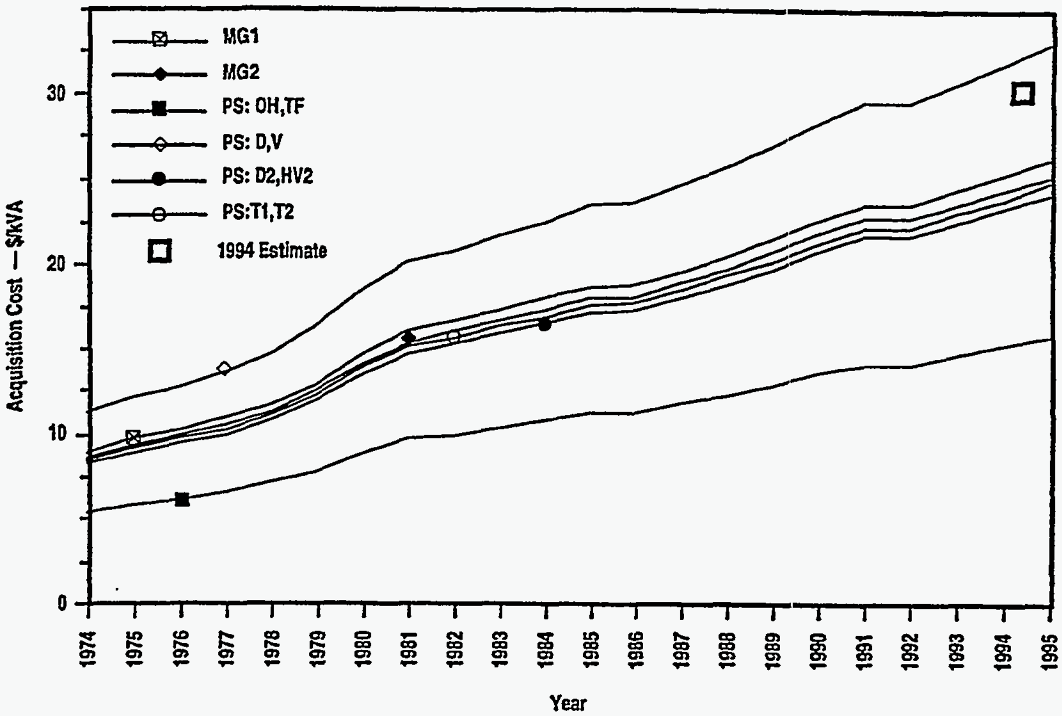

Fig. 3. Cost Trend for DIII–D Power Supply Equipment

availability (actual operating time relative to scheduled operating time) of the DIII–D tokamak systems is being monitored during each operation period. During the past five years (1990 through 1994), the tokamak system availability has ranged from 71.4% to 78.3% with no clear trend of improvement. The down time for the tokamak is allocated to six categories; Computers, Vacuum Systems, Diagnostics, Neutral Beams, Power Systems, and Other. The percent down time for each of these categories is plotted in Fig. 4.

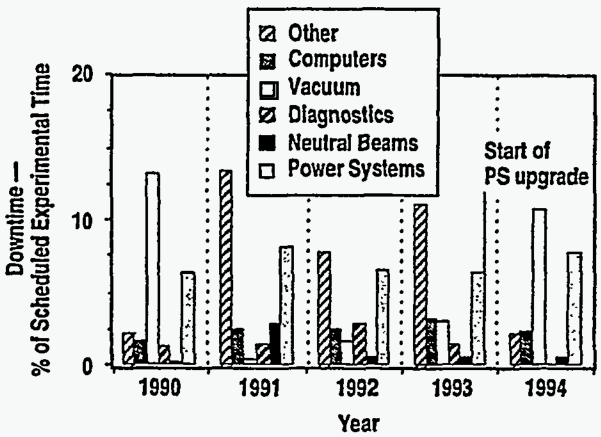

Fig. 4. DIII–D Operations Downtime

Upgrades to the TF and OH Power Systems

Failure reports and associated downtime records are used in planning upgrades to the electrical systems. The TF and OH power supplies were the first power supplies to be upgraded under this plan. A significant number of problems associated with these power supplies were due to malfunctions of the old 15 kV vacuum circuit breakers during the last two years of operation. New 15 kV "rack-out" vacuum circuit breakers were therefore installed in these power supplies. Vacuum circuit breakers are typically rated for 10,000 interruptions if properly maintained (it is usually the actuator mechanism which wears out prematurely in the breakers in service at DIII–D). The newly installed circuit breaker modules can be exchanged in a few minutes time in the event of malfunction.

Mechanical vibration due to the magnetic forces between high current conductors was the source of fatigue fractures of printed circuit card component leads in the SCR gate drive circuit assemblies for both the TF and OH power supplies. New gate driver cards were designed and tested to endure in this vibration environment. They were then installed in the TF power supply. New gate drive cards will also be installed in the OH power supply in spring of 1995.

Worn and corroded relay contacts had also become sources of intermittent malfunctions in the control circuits for the TF and OH power supplies. These relay control and monitoring circuits were therefore removed and replaced with modern programmable logic controllers (PLC).

Load sharing between parallel power supply modules in the TF and OH power supplies had been a frequent cause of premature shutdowns. This problem was solved by using the same SCR gate control signal timing in all the power supply modules.[3] These signals were transmitted from the system control to the individual modules via fiber optic links. This common controller ensured the best achievable current sharing between the parallel modules. This scheme also produced perfect dynamic and steady-state voltage sharing between the series connected power supplies in the TF power system.

Upgrades to the PF Coil Power System

The dc power supplies in the field shaping coil system are also line-commutated power supplies. The old control systems in these power supplies have been significant sources of downtime and will also be upgraded on a priority basis. Problems with the control interfaces to the poloidal field coil power supply system have already been solved with the installation of a new programmable controller based CAMAC interface.

The choppers in the PF power system were originally designed for a 0.5 second pulse rating, and have gradually been upgraded to 5 s pulse duration capabilities at full power. If any of these choppers malfunction during a shot, then the shot fails. These choppers impose limits on the DIII–D operation space and contribute to the down time for the power systems. Our plan includes the upgrade of the choppers to 10 s pulse length capability and improving their reliability in operation.

Power System Interlock and Protection

A power supply interlock and protection system (EPSSIC) monitors the status of the many tokamak systems and provides enabling commands to the OH power system and the polarity reversing switches in this circuit. EPSSIC provides an abort command to the OH power supply whenever any of the tokamak operating limits are not satisfied during a discharge, causing the power supply system to shut down. The EPSSIC which was almost entirely based on relay logic had also become unreliable and has been replaced with a PLC which is interfaced to the operator control console via a microprocessor controlled interface card.

Recent Operational Experience

The improvements which were immediately noted and appreciated were associated with the operator interfaces. In particular, the new EPSSIC and the PF system CAMAC interface were enthusiastically received because of the improved reliability and functionality they provided. Downtime associated with the TF and OH power supplies have also been essentially eliminated. A major source of downtime, however, remains the PF power system dc power supplies and the choppers.

New operational flexibility from the controller in the TF power supply provided the capability to exchange the output current to the toroidal field coil between the two series connected power supplies in this circuit.[3] Diodes which are used to provide a bypass current path for the power supplies in this mode were originally installed for TF coil protection. This new control feature is used to improve the input line power factor to the power supply by turning off one of the two series connected converters after the TF-field flattop has been attained, and has doubled the operating space of the DIII–D toroidal field power supplies. The new controller accomplishes this action by turning the SCR gates off in one of the power supplies, causing the remaining active power supply to adjust its output voltage accordingly via the common controller. A shot which demonstrates this capability is shown in Fig. 5. The unused supply can return to service later in the discharge when the first supply has reached its thermal limits.

Power Supply Models for Control Design

A new integrated plasma control system is being designed for DIII–D. This plasma control system uses new advanced control methods which are based on knowledge of the control characteristics of the power supply systems, coil/vessel system, and the plasma. Models have been prepared for the DIII–D electrical systems and validated in tests.[4] These models are now being used in plasma control simulations. A chopper voltage controller shown in Fig. 6 is based on these models. Figure 7 shows the model for the chopper block in this voltage controller. A small signal perturbational model of the chopper is compared with test data in Fig. 8. Figure 9 compares the voltage controller in Fig. 6 with measured data, and shows good agreement between the model predicted response data and the measured response.

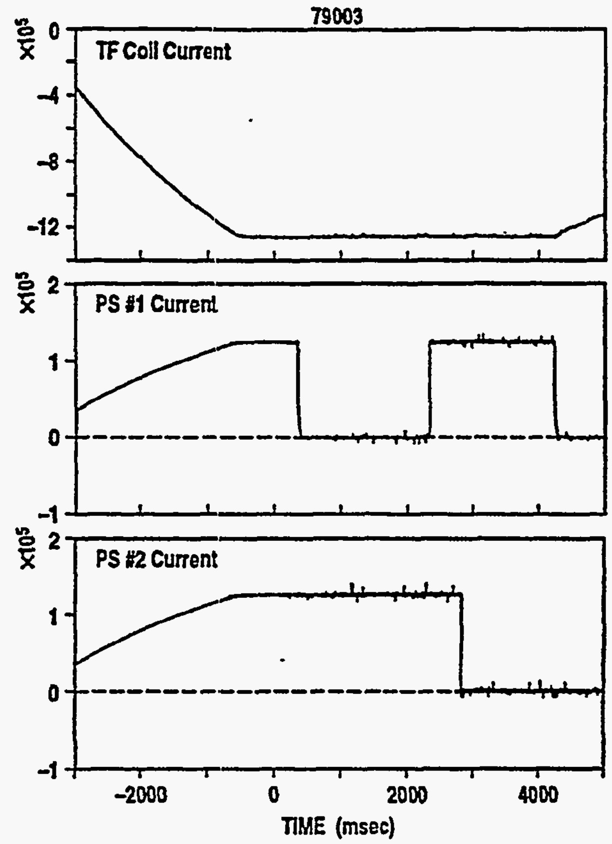

Fig. 5. TF Power Supply Current Transfer

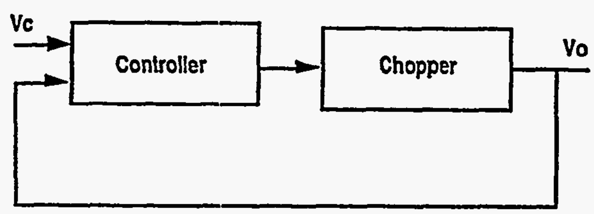

Fig. 6. Chopper Voltage Control Model

Summary

Costs for the DIII–D power systems have been provided, and the cost trends for this equipment tracks the U.S. Consumer Price Index with respect to cost escalation. Recent upgrades of the DIII–D OH and TF coil power supply systems have improved the availability and operational flexibility of these systems. Upgrade of the PF power system control systems have been planned to take place over the next two years. Power system models have been developed

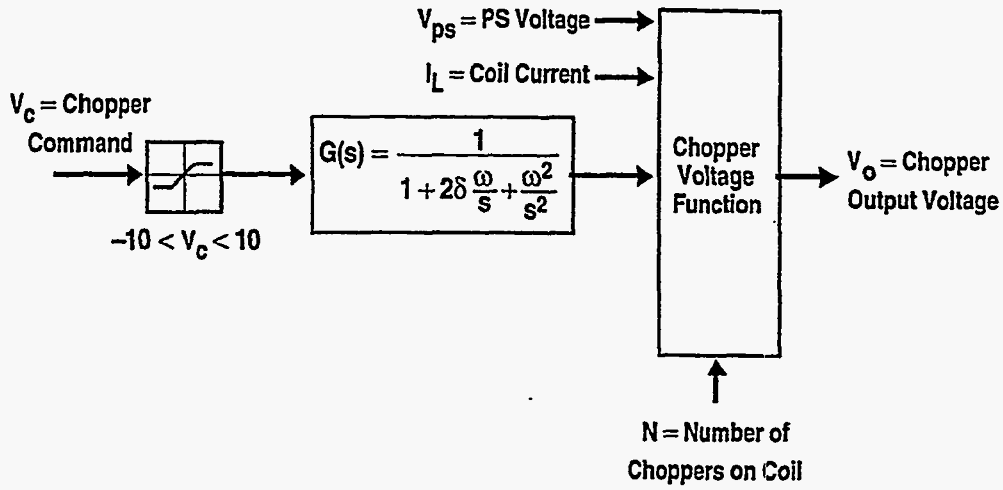

Fig. 7. Chopper Model

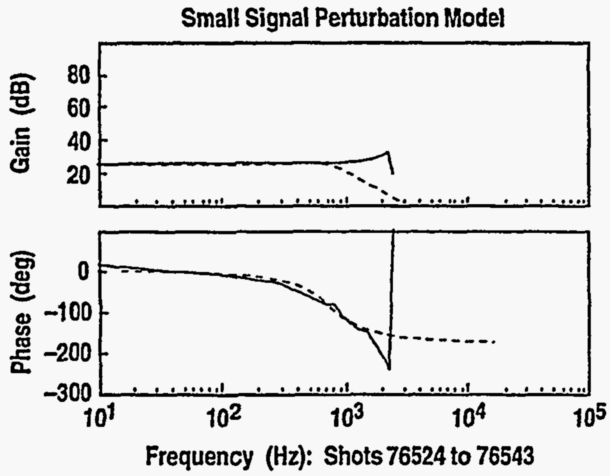

Fig. 8. Chopper Model Response vs. Test Data

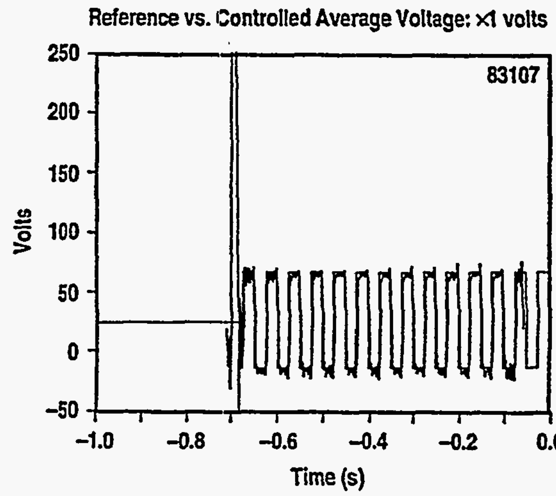

Fig. 9. Chopper Voltage Controller Response v.s. Test Data

which are being used in the development of an integrated controller in preparation for the Advanced Divertor and Advanced Tokamak research programs.

Acknowledgment

This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114.

References

[1] A. Nerem, "State of the Art and Problems of AC/DC Conversion at ITER-Scale Power Levels," presented at First ITER Power Supply Meeting, May 1994, Naka, Japan.

[2] A. Nerem, E.E. Bowles, S. Chapelle, R.J. Callanan "Advanced Power Conditioning for Maglev Systems Final Report," General Atomics, PB93-150274, NTIS.

[3] P.M. Petrach, A.R. Rouleau, R.D. McNulty, D.B. Patrick, J.L. Walin, "Upgrade of DIII–D Toroidal Magnetic Field Power Supply Controls," Proceedings of the 15th IEEE/NPSS Symposium on Fusion Engineering, Vol. 2 (1993) p. 893.

[4] M. Walker, A. Nerem, D. Baggest, "Advanced Plasma Control IR&D Final Report Part 1, DIII–D System Models for Feedback Control," General Atomics Report GA–AA21745 (1995).