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Retrofitting Utility Power Plant Motors for Adjustable Speed: Field Test Program

Prepared by
Bechtel Group, Inc.
San Francisco, California

REPORT SUMMARY

SUBJECTS	Power electronics / Load/energy management and controls
TOPICS	Adjustable-speed drives Power electronics Motors Harmonics Demand-side management
AUDIENCE	Utility marketing and research engineers / Utility power plant engineers

Retrofitting Utility Power Plant Motors for Adjustable Speed: Field Test Program

Advances in power electronics technology have improved the reliability and reduced the cost of electronic adjustable-speed drives (ASDs). This report, based on a five-year field test, offers detailed advice on how to retrofit power plant motors with ASDs to improve system performance and reliability, minimize equipment stress, and reduce system operating costs.

BACKGROUND Multimegawatt induction motor ASDs are in use at more than 200 installations. Many more plants are currently being retrofitted with ASDs. EPRI began a field test program for large motor ASDs in 1981 at five test generating units to evaluate energy savings available through this technology and to learn the best ways to undertake retrofits.

OBJECTIVES To provide guidance on how to implement ASD retrofits successfully; to evaluate the actual energy savings from each application; and to assess the impact an ASD can have on the power quality of the power plant's electrical distribution system.

APPROACH Researchers selected five applications that offered good potential for energy savings and operational improvement. The project was directed toward applications with ac motor drives that exhibit a load duty cycle conducive to demand-side management (primarily strategic energy conservation) through ASD technology. Power electronics equipment retrofits eliminated the need for control by valve or inlet vanes and the power losses associated with these devices. One of the selected sites was the first full-scale application of ASDs in the main cycle of a plant using sliding-pressure operation. The ASD was installed on a boiler feedpump. Over a five-year period, researchers gathered operating data at these installations with and without the ASDs in operation to establish the actual energy savings resulting from ASD use. They also gathered power quality data in the field to assess the impact of ASDs on the electrical distribution system.

RESULTS The ASDs were used in gas-, oil-, and coal-fired plants. The associated cooling systems included direct air cooling with filters, air cooling with air conditioners, air cooling with air/water heat exchangers, and water cooling.

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ABSTRACT

EPRI recognized there was a need for converting large power plant induction motors to adjustable speed for fuel conservation. When this project started, only the synchronous motor ASD was available which required a new synchronous motor to replace the existing squirrel cage motor. The retrofitting of large power plant induction motors offered an opportunity to develop and refine a technology for large induction motor ASDs.

Prior to 1984 no high horsepower induction motor ASDs were installed on utility or industrial fans or pumps, but there were 57 LCI synchronous motor systems. By mid-1986 the market evolved such that more induction motor ASDs were being installed in the U.S. than synchronous motor ASDs.

The major U.S. induction motor ASD suppliers now offer water cooling which greatly simplifies the cooling of large thyristors in power plant environments.

Included in the report is a copy of a sample ASD specification developed during the field test program. The other major output of this study, ASCON II, an IBM PC compatible computer program for technical and economic applications of ASDs to power plants, has been improved as a result of these field tests and will be made available from the Electric Power Software Center.

ACKNOWLEDGMENTS

We wish to acknowledge the fine work of Bechtel National, Inc. engineers who participated in developing the measurement technique for power and harmonics in the electrical systems during the field tests. They are Dr. Tim Yen, Nickolas Krause and A. Ali Eslami. Mr. Eslami recorded all the measurements during the on-site field tests. Also, thanks to the utility engineers who devoted much time and effort to conduct the tests, in particular the following:

Sierra Pacific Power
George Tatar - Ft. Churchill Plant tests
Ron Van Limberg - Tracy Plant tests

Gulf States Utilities
Dennis Broussard - Willow Glen Plant tests

Oklahoma Gas & Electric
Steve Puckett - Seminole Plant tests

Iowa Public Service Company
Dana Ralston and Gene Kempers - Neal Plant tests

Fred Tajaddodi of Bechtel Power Corporation produced the analytical verification of the test method of Appendix A.

The support and encouragement of the sponsors of this work, EPRI, with Ralph Ferraro, Ben Banerjee, and Marek Samotyj are gratefully acknowledged.

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Executive Summary

EXECUTIVE SUMMARY

This research program studied the application of high power adjustable speed drives (ASDs) to auxiliary motors of utility electric generating stations. Four utilities participated in field tests of these large ASDs on boiler feed pumps and forced draft fans.

In the period of the field tests, 1984 to 1989, rapid advances have been made in the technology of ASDs for large induction motors. The principal gains arose from new schemes for commutating the inverter. Vector control has also been introduced to allow separation of motor flux control and motor current control to allow the control of torque separately from voltage.

The field tests were conducted at the following installations with the inverter technology indicated:

- Sierra Pacific Power Co.
  1-2000 HP boiler Feed Pump current-source
  ASD at Ft. Churchill Plant, Unit 2

- Gulf States Utilities
  1-2250 HP Boiler Feed Pump modified LCI
  ASD at Willow Glen Plant, Unit 1

- Iowa Public Service Co.
  2-6300 HP Boiler Feed Pump modified LCI
  ASDs at George Neal Plant, Unit 2

- Oklahoma Gas & Electric Co.
  2-5000 HP FD Fan current-source, GTO-PWM
  ASDs at Seminole Plant, Unit 1

- Sierra Pacific Power Co.
  1-2000 HP Boiler Feed Pump, current-source GTO-PWM
  ASD at Tracy Plant, Unit 3

These five field test projects use the existing power plant squirrel cage induction motors. The power electronics equipment additions allow control of feedwater flow or air flow directly by motor speed, thus eliminating the control valve or inlet vanes and the power losses associated with these devices.

The test program observed the performance of the equipment operating with ASD control. Power measurements were made to verify power savings and economics. Harmonics were measured at the input and output of the ASD. Motor vibration was measured over the speed range. Current and voltage wave shapes were recorded and means were established to determine ASD efficiency. Several ASD cooling systems and enclosures were evaluated in the course of the test program. Economic results are summarized in Table S-1.

These tests occurred over a five year period. During this time modified load-commutated inverters and the current-source GTO-PWM inverters have been installed in over 200 installations nation-wide, ranging from 600 HP to 9000 HP. GTO stands for Gate Turn-off Thyristors; PWM stands for pulse-width modulated - a technique for creating low harmonic content ac waveforms.

These field tests have yielded a wealth of information on the application of this new technology to large power plant induction motors. Among the lessons learned in this work are the following:

1. The potential for operating cost savings by controlling process flow with motor speed has been demonstrated by test.

2. Reliability of large ASDs has ceased to be an issue. Several improvements in ASDs that have developed directly from operating experience have contributed to improved overall system reliability:

   --An input transformer is now used on all large ASD installations to control common-mode voltage.

   --Shaft torsional resonance caused by interaction of the ASD output capacitor filter and the motor winding is now understood and can be controlled either by eliminating harmful output harmonics with the GTO-PWM ASD or a 12-pulse inverter or by separating the electrical and mechanical resonance frequencies with an output reactor.

   --Power electronic devices, like thyristors and GTOs, have proven to be robust and reliable when correctly applied.

   --Available control systems have proven to provide trouble-free service.

3. With an input transformer, harmonics to the power plant auxiliary bus can be kept to under 3 percent total voltage harmonic distortion, in most cases. This harmonic level does not appear to cause interference with other power plant control systems.

4. During these tests, for the inverter technology used in these ASDs, it has not been necessary to derate the induction motors with ASD control.

Table S-1

ECONOMIC SUMMARY ASD RETROFITS

STATION	ASD APPLICATION	ANNUAL SAVINGS	YEARS PAYBACK
FT. CHURCHILL	2-1000 HP BOILER FEED pp	$1,600,000	.3
WILLOW GLEN	1-2250 HP BOILER FEED pp	130,000	2.5
NEAL	2-7000 HP BOILER FEED pp	348,000	7.7
SEMINOLE	2-4000 HP FD FANS	231,000	5.4
TRACY	1-2000 HP BOILER FEED pp	80,000	3.4

5. Boiler feed pumps in sliding pressure applications (e.g. in which boiler pressure is reduced with load) can benefit from conversion to ASD control both from power savings and reduced valve maintenance.

6. The power savings obtained in using ASD control of process flow in power plants has been shown to improve heat rate in fossil power plants.

7. Experts agree that reduced heat rate translates to reduced stack emissions. This benefit of ASDs was identified in the IPS boiler feed pump ASD test. ASDs reduced auxiliary load by 2.4 MW at full load. This additional unit output is considered to be pollution free generation.

8. The soft start of induction motors with ASD control has several benefits:

   -- The hydraulic surge from across-the-line starting of pumps has been eliminated. This can benefit high pressure pumps with tight seal clearances.

   -- The windings of older motors benefit from extended life with the elimination of thermal and magnetic surges.

   -- By eliminating the thermal transient in the rotor with the ASD soft start and by using the ASD to produce frequencies up to 167 hz, new induction motor designs are available to 10,000 HP, 10,000 rpm. Previously, the practical horsepower and speed limits were 3500 HP, 3500 rpm.

   -- With the soft start, the induction motor rotor is not subjected to main power frequency currents. A laminated rotor is no longer necessary for high speed induction motors, resulting in improved mechanical performance.

Utilizing the information gained from these tests, a preferred configuration for a power plant specific ASD has evolved. This configuration has the following features.

- Input transformer to control input harmonics and line-to-ground voltage at the motor.
- UPS system for clean power to the ASD control system to eliminate adverse effects from voltage spikes, dips, and interruptions on ASD performance.
- Water-cooled thyristors to simplify cooling of the ASD in the often hot, dusty environment of power plants.
- GTO thyristor inverter to control harmonics to the motor in order to eliminate shaft torsional resonance.
- Ground between inverter and motor to control line-to-ground voltage at the motor used in combination with input transformer.

The preferred configuration for a large power plant induction motor ASD is shown in Figure S-1.

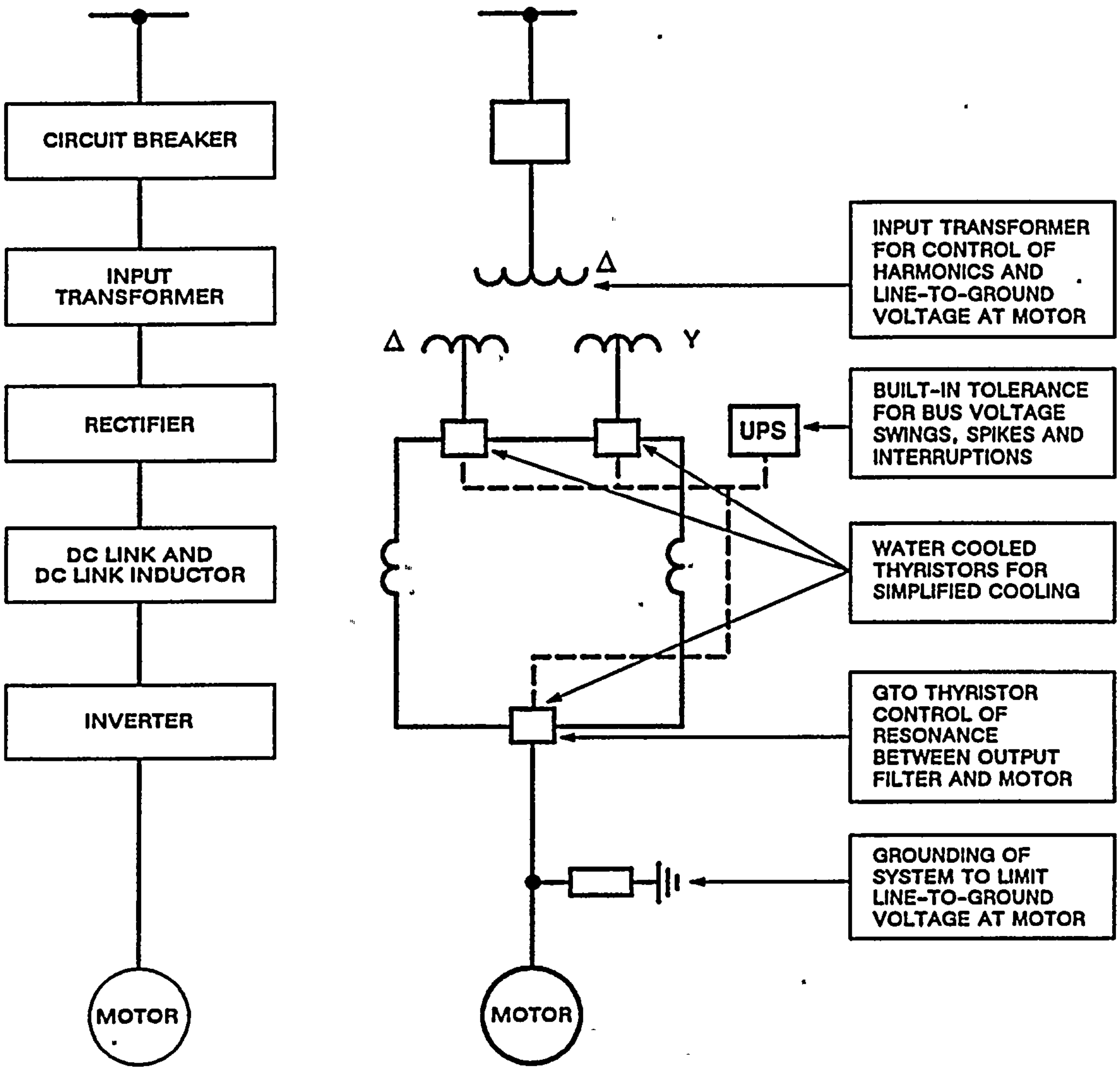


Figure S-1

PREFERRED CONFIGURATION FOR LARGE POWER PLANT ASD

1. Introduction

Section 1

INTRODUCTION

In December 1984 Sierra Pacific Power Company started up a 2000 HP adjustable speed drive (ASD) on the 1750 HP 2A boiler feed pump motor at its Ft. Churchill Plant in Yearington, Nevada. This ASD is configured as a 12-pulse input, 12-pulse output current-source system. A year later in January 1985 Gulf States Utilities Inc. began operating a 2250 HP ASD on its 1A boiler feed pump at Willow Glen Plant at St. Gabriel, LA. This ASD is a 6-pulse input, 6-pulse output, modified load-commuted inverter. This modified LCI system operates in the LCI mode from 50% to 100% speed and operates with a dc link commutation circuit at lower speeds.

These installations were followed in 1988 by 2-5000 HP ASDs on FD Fans at Oklahoma Gas & Electric's Seminole Plant and 2-6300 HP Boiler Feed Pump ASDs at Iowa Public Service Company's George Neal Plant. A fifth ASD Installation was at Sierra Pacific Power Company's Tracy Plant, Unit 3, 1750 HP Boiler Feed pump in 1988. These last three installations used the new gate-turn-off thyristor technology in the inverter section of the ASD.

These field tests culminate an eight year program of studying the retrofit conversion of existing fixed speed induction motors in power plants to adjustable speed with power electronics. Earlier in this program, work included the following:

- Evaluation of the economics of retrofitting large motors in 50 generating units for adjustable speed. This study showed that ID Fans, FD Fans, Condensate Pumps, and Primary Air Fans could benefit from conversion to adjustable speed, depending on fuel cost and annual load duration curve. Boiler feed pumps, when converted to adjustable speed, experience excellent savings at low load if ASDs are used to reduce both feedwater flow and boiler pressure (sliding pressure or sliding throttle).

- Development of a computer program ASCON II to calculate fuel cost savings in power plants when converting motors to adjustable speed.

- Worldwide assessment of ASD technology and determination of equipment costs and installation costs. Inverter technology available in the higher than 2000 HP class of equipment was current-source, voltage-source, modified load commutated, voltage-source GTO-PWM, and current-source GTO-PWM.

- Assessment of ASD reliability which showed that correctly designed equipment based on manufacturer's systematic and continuing quality control programs provide outstanding reliability.

2. Field Test Program

Section 2

FIELD TEST PROGRAM

The field test program followed the earlier ASD technology evaluation and application study program and included five power plant retrofit projects:

- 1984
Sierra Pacific Power Co.
1-2000 HP Boiler Feed Pump current-source
ASD at Ft. Churchill Plant, Unit 2

- 1985
Gulf States Utilities
1-2250 HP Boiler Feed Pump modified LCI
ASD at Willow Glen Plant, Unit 1

- 1988
Oklahoma Gas & Electric Co.
2-5000 HP FD Fan current-source, GTO-PWM
ASDs at Seminole Plant, Unit 1

- 1988
Iowa Public Service Co.
2-6300 HP Boiler Feed Pump Modified LCI
ASDs at George Neal Plant, Unit 2

- 1988
Sierra Pacific Power Co.
1-2000 HP Boiler Feed Pump, current-source GTO-PWM
ASD at Tracy Plant, Unit 3

These five field test projects retrofitted existing power plant squirrel cage induction motors. Power electronics equipment has been added to control feedwater flow or air flow directly by adjusting motor speed, thus eliminating the need for control valve or inlet vanes and the power losses associated with these devices. In conducting these tests EPRI was interested in determining the following information:

- Power to the ASD and to the motor
- Voltage and current harmonics injected into the motor and into the auxiliary power systems
- Additional motor losses from harmonics
- Vibration from mechanical resonance in system

- ASD efficiency
- Verification of calculated fuel cost savings
- Reduction of fan noise
- Control input harmonics to 3% voltage THD level
- Identification and quantification of any other benefits from the use of ASDs.

In the following Sections Three through Eight, each of the five field tests is described and the test results are presented.

3. Sierra Pacific Power Company
Ft. Churchill Plant
Unit 2, Boiler Feed Pump
2000 HP ASD Field Test

Section 3

SIERRA PACIFIC POWER COMPANY, FT. CHURCHILL PLANT UNIT 2, BOILER FEED PUMP, 2000 HP ASD FIELD TEST

UNIT DESCRIPTION

Ft. Churchill Plant Unit 2 is a 110 MW gas and oil fired unit. As a spinning reserve unit, it is operated for over 8000 hours per year at minimum load.

PURPOSE OF PROJECT

The purpose of converting the 2A Boiler Feed Pump to adjustable speed was as follows:

- Reduce minimum load on the unit by 2 MW and replace the 2 MW by lower cost power.
- Eliminate the control valve at the feed pump discharge thereby eliminating both the power loss in the valve and the associated valve maintenance cost.
- Convert the low load operation of the unit to sliding throttle (reduce boiler pressure from 1750 psi to 700 psi at low unit load operation).
- Extend the MW output of the unit from 70 MW to 90 MW with one pump operating.
- Provide automatic drum level control for all operating conditions. Drum level is vital to the operation of the boiler and had been difficult to hold at Ft. Churchill because of limited capability of the control system at minimum load. The boiler drum is a high pressure water tank located at the highest part of the boiler. Water in the drum keeps a positive head of water on the boiler tubes.

DESCRIPTION OF APPLICATION

The 2000 HP ASD was connected in line with the existing 2A Boiler Feed Pump Motor as shown in Figure 3-1. A manual electrical by-pass circuit was provided to allow operation of the motor without the ASD in event of serious long term ASD outage. The common control valve for the 2A and 2B Boiler Feed Pumps was relocated to the discharge of the 2B pump. The before and after valve location is shown in Figure 3-2. With this arrangement, the 2A pump with ASD control is used for

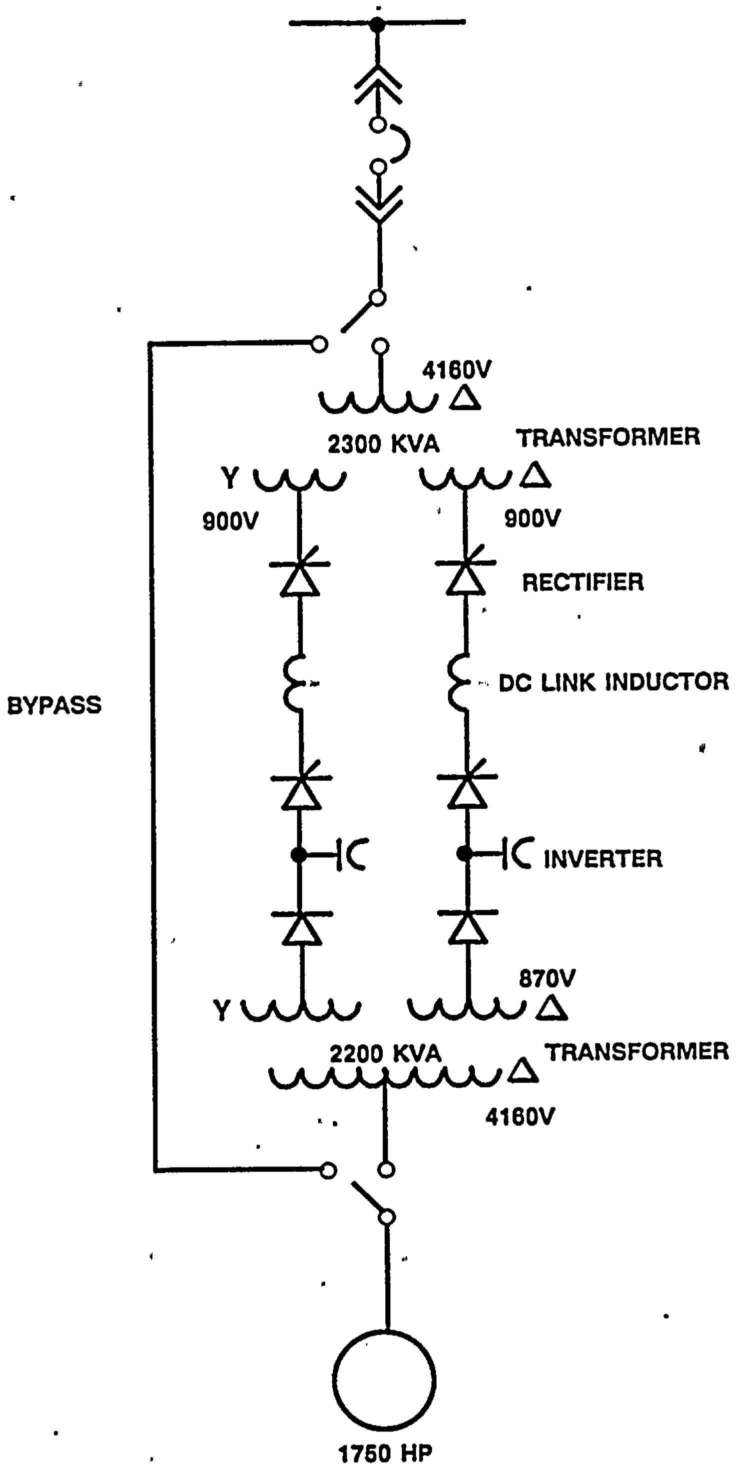
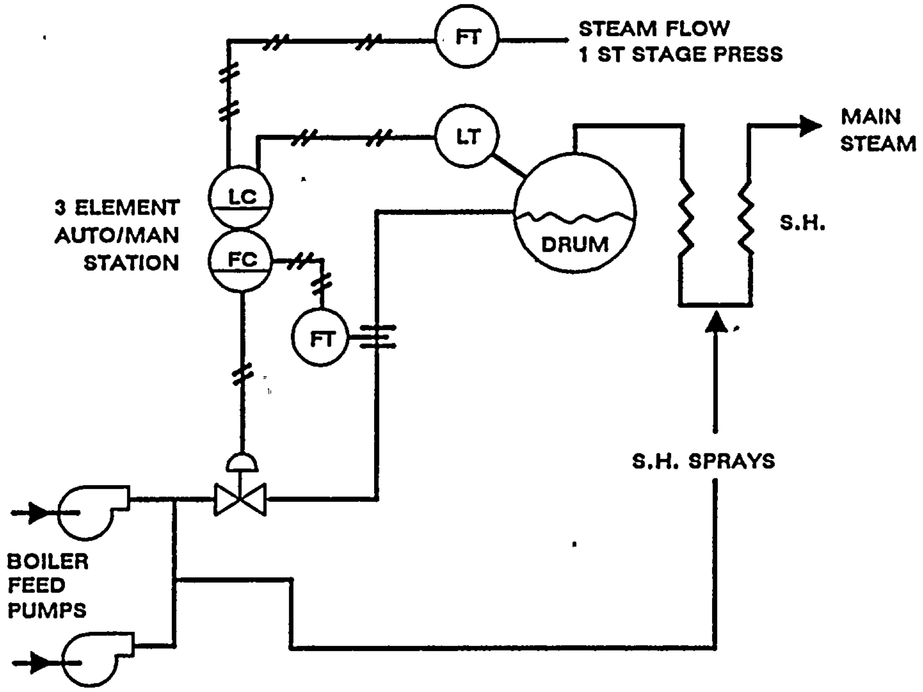


Figure 3-1
FT. CHURCHILL PLANT, UNIT 2
12-PULSE CURRENT SOURCE ASD



FEEDWATER CONTROL SCHEME BEFORE INSTALLATION OF ASD

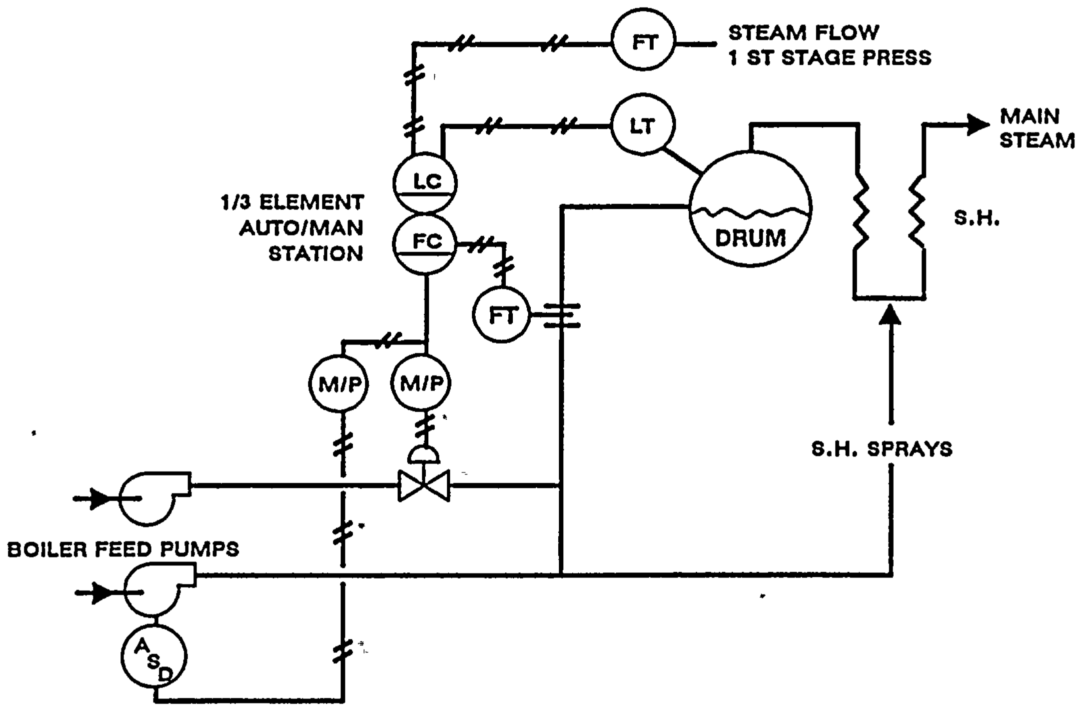


Figure 3-2
FEEDWATER CONTROL SCHEME WITH 2B BFP ON SPEED CONTROL

normal unit operation which is a minimum load, spinning reserve mode. The 2A pump is used for loads up to 90 MW. Above 90 MW, the 2B pump is operated with the control valve wide open and the 2A pump is backed off and is used for control.

ASD TECHNOLOGY

The ASD used for this project has a current-source type inverter with input and output transformers to control harmonics to the 4 kV bus and to the motor. The ASD requires no input filters or output filters. Solid state, digital microprocessor type control and diagnostics are used. The power circuit for this ASD is shown in Figure 3-3. One unique feature of this ASD is that it has one thyristor in series per leg in both the rectifier and in the inverter.

OPERATING EXPERIENCE

The ASD has been in service since December 1984. There were no operating problems with either the ASD or the control system until 1987. In 1987, there were heavy thunderstorms nearly every day for a period of six weeks. During some of these storms there were thyristor failures in the ASD that caused loss of the unit. It appears that these failures resulted from depressed bus voltage from transmission line faults from the lightning. The voltage was low enough to affect the ASD firing controls and failures resulted.

A schematic of Ft. Churchill Unit 2 is shown in Figure 3-4. The automatic drum level control afforded by the ASD has been excellent in terms of reliability and quality of control function. Plant operators accepted enthusiastically the ASD automatic control of the drum level from the first days of operation and have kept this attitude for the five years of operation of the ASD. An isometric view of the ASD installation is shown in Figure 3-5.

RESULTS OF RETROFIT

The unit output was reduced by 4 MW. At normal minimum load operation boiler pressure is held at 700 psi, down from the designed 1890 psi. Dollar savings have been estimated at $1.6 million per year by Sierra Pacific Power. Half of this is from savings of generating the 4 MW elsewhere and half from better operating efficiency at 700 psi.

The wave shapes that were recorded at Sierra Pacific Power, Ft. Churchill Plant are shown in Figure 3-6. The advantage of the 12-pulse system is seen in the Fourier analysis of Figure 3-7. On the input or rectifier side there are

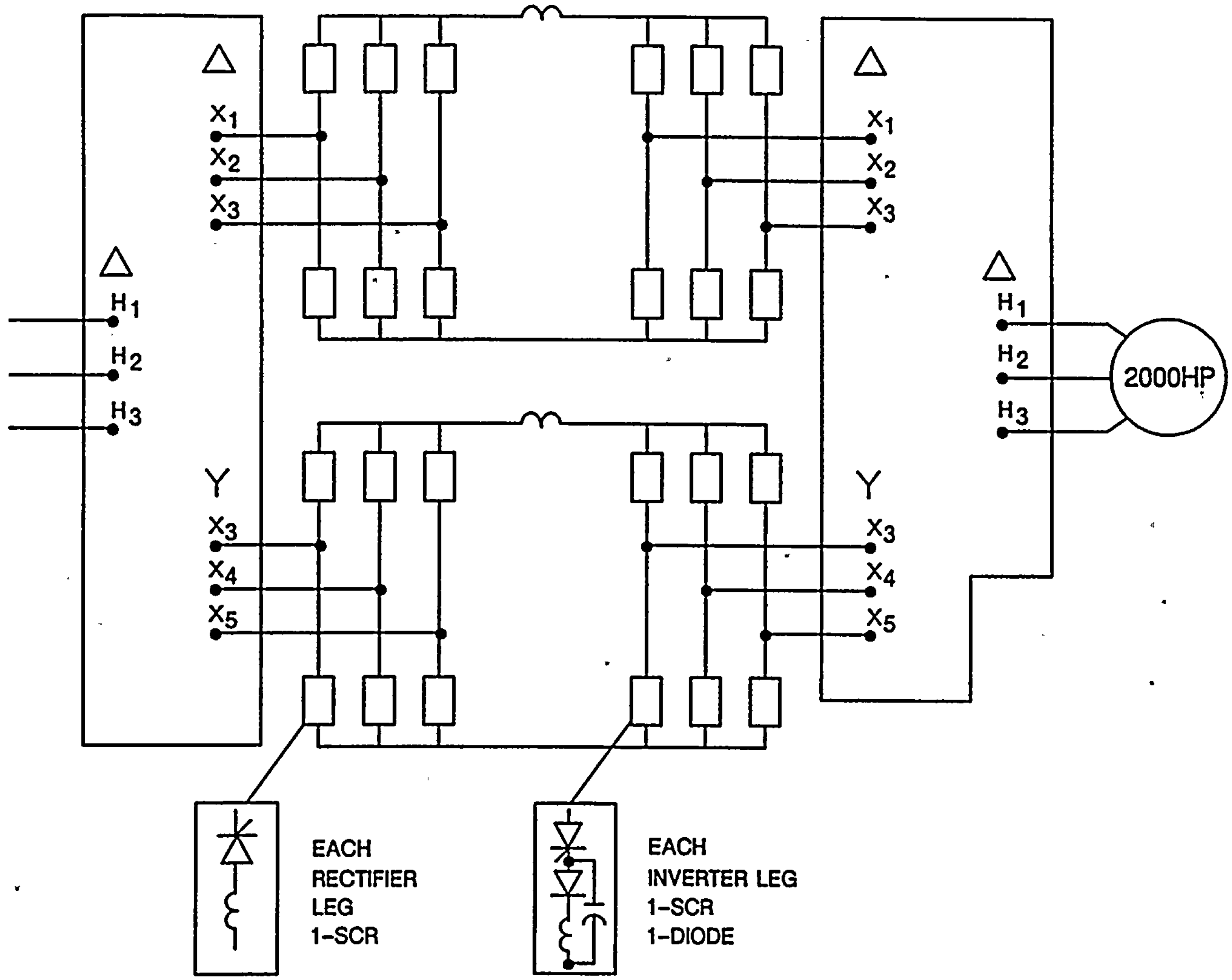


Figure 3-3

FT. CHURCHILL PLANT
2000HP CURRENT SOURCE 12-PULSE ASD

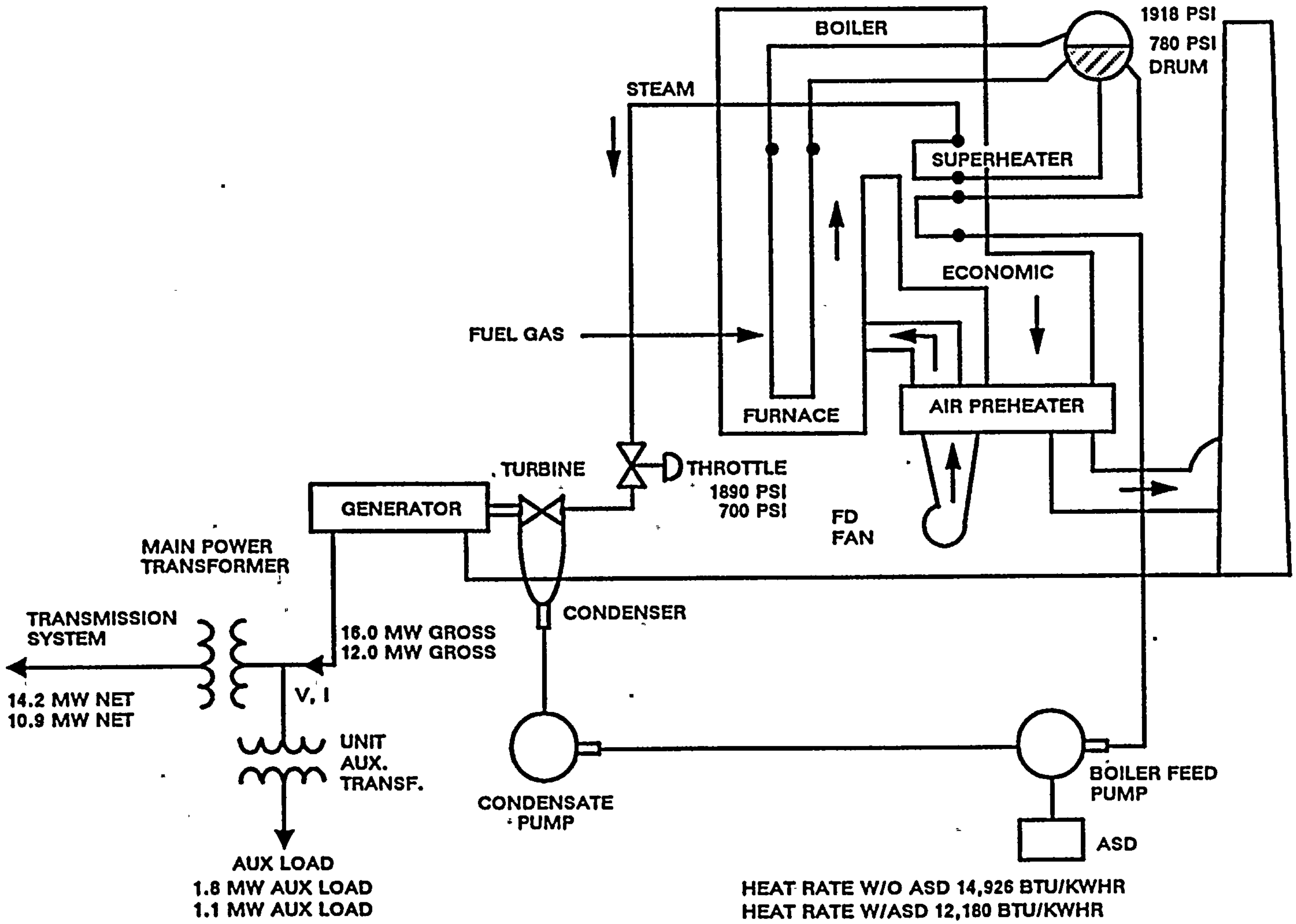


Figure 3-4
SIERRA PACIFIC POWER CO.
FT CHURCHILL, UNIT 2
BOILER FEEDPUMP ASD

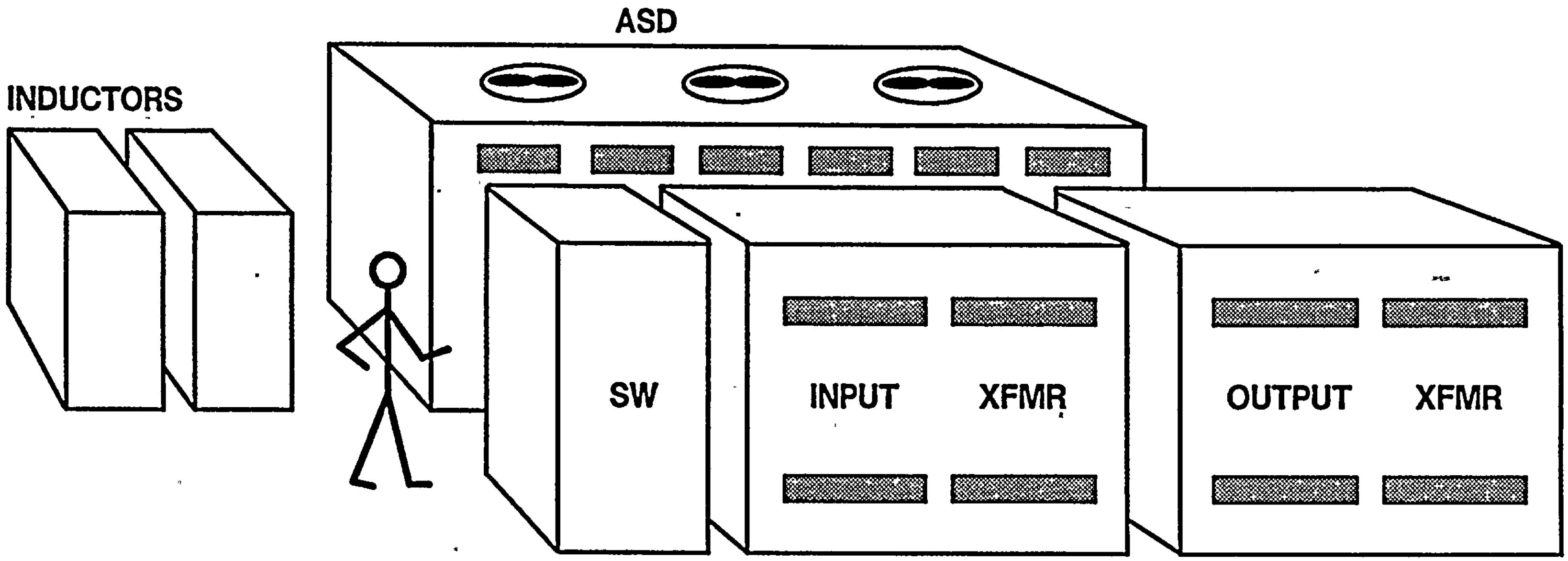


Figure 3-5
FT CHURCHILL UNIT 1
ISOMETRIC VIEW ASD INSTALLATION

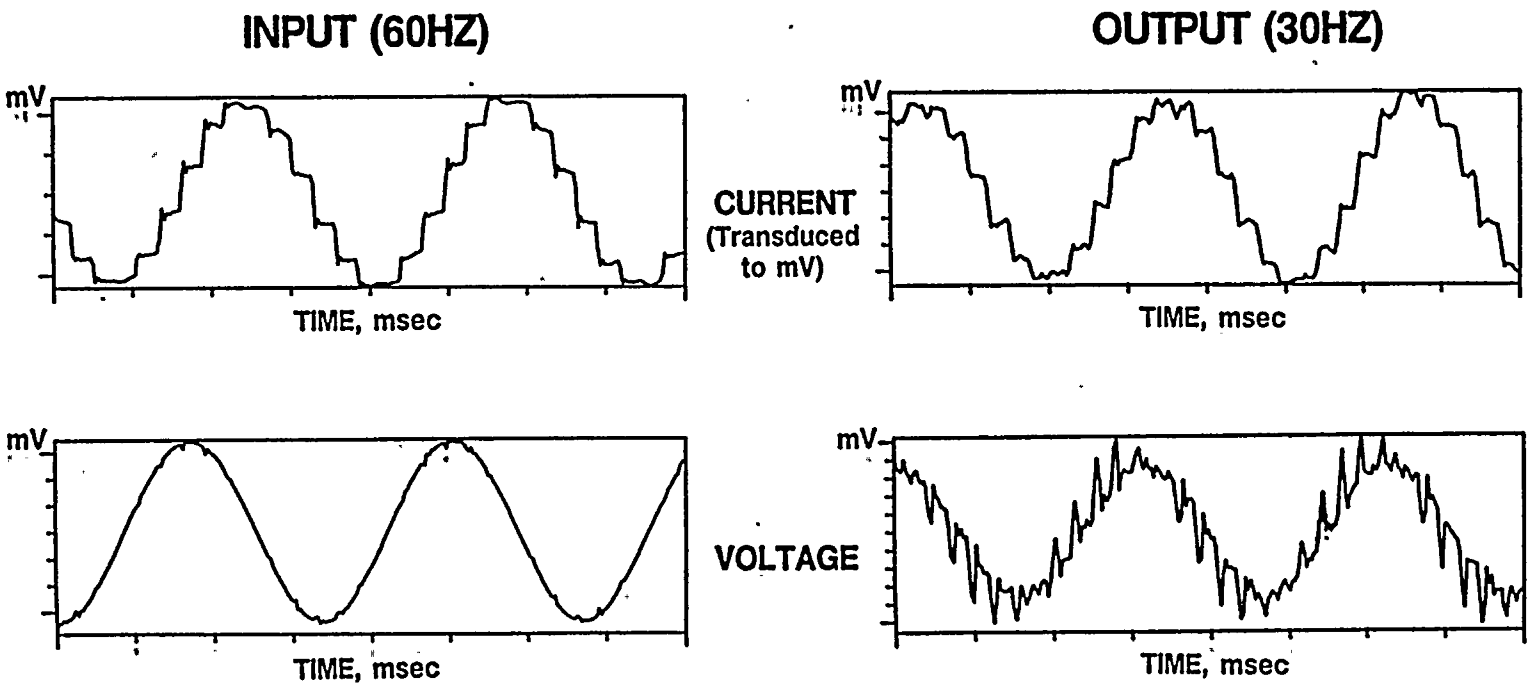


Figure 3-6
CURRENT SOURCE ASD
12-PULSE INPUT, 12-PULSE OUTPUT
(AT 30HZ OUTPUT)

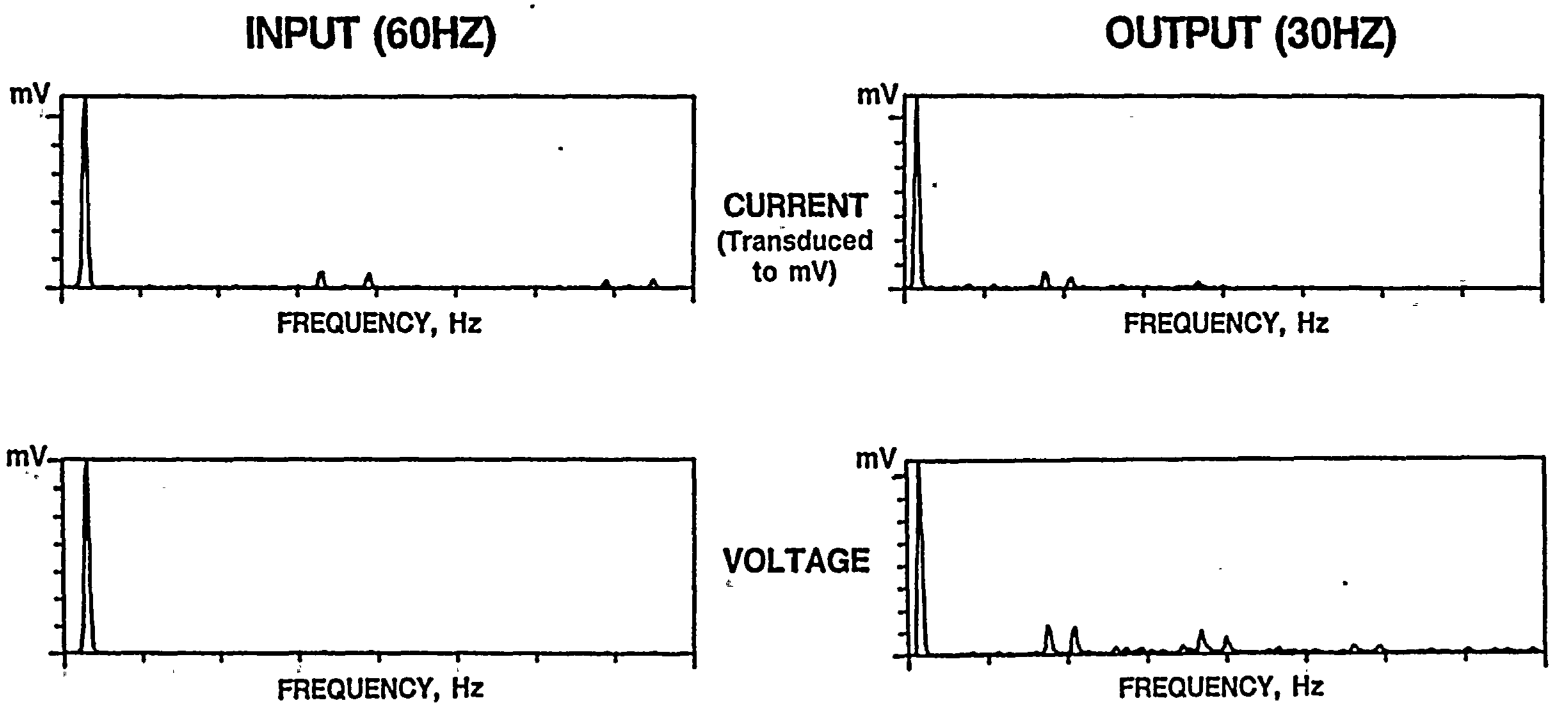


Figure 3-7
CURRENT SOURCE ASD
12-PULSE INPUT, 12-PULSE OUTPUT
FOURIER ANALYSIS OF INPUT AND OUTPUT
(AT 30HZ OUTPUT)

practically no voltage harmonics and the order of the current harmonics seen were 11, 13, 17, 19. The order of the output current harmonics were 11, 13 and small 17, 19. The output voltage contained 11th and 13th order harmonics.

The analysis of the field measurements taken at Sierra Pacific Power are shown in Table 3-1.

To determine the heat rate and dollar savings at Ft. Churchill Plant, Sierra Pacific engineers conducted a study which is discussed in Appendix C.

Table 3-1

FT. CHURCHILL, UNIT 2
1750 HP BOILER FEED PUMP
FIELD RESULTS

UNIT MW	HP	MOTOR FREQ.	RPM	% EXTRA MOTOR LOSS	HARMONICS				ASD EFF
					INPUT		OUTPUT		
					THD-V	THD-I	THD-V	THD-I	
90	1897	60.2	3576	.7	2.4	10.7	10.6	9.3	.91
75	1380	55.8	3315	.9	2.3	11.0	16.4	9.6	.91
50	1058	52.5	3119	1.0	2.1	11.4	16.0	9.4	.91
25	769	50.3	2989	1.1	1.86	11.9	16.7	9.5	.89
12	204	31.7	1883	1.7	1.0	10.9	24.6	8.6	.82

4. Gulf States Utilities
Willow Glen Plant
Unit 1, Boiler Feed Pump
2250 HP ASD Field Test

Section 4

GULF STATES UTILITIES, WILLOW GLEN PLANT
UNIT 1, BOILER FEED PUMP, 2250 HP ASD FIELD TEST

UNIT DESCRIPTION

Willow Glen Unit 1 is a 146 MW unit located on the Mississippi River south of Baton Rouge, LA. It is designed for gas or oil fired operation.

PURPOSE OF PROJECT

Gulf States Utilities decided to convert one of the 2-2250 HP Boiler Feed Pumps at Willow Glen, Unit 1 to adjustable speed operation for the following reasons:

- improve unit heat rate by eliminating the power loss in feed pump control valve.
- eliminate control valve maintenance by relocating control valve to the 2B pump.
- obtain experience with large adjustable speed drives for consideration in other generating units.

DESCRIPTION OF APPLICATION

After observing the ASD in operation at Sierra Pacific Power Company at Ft. Churchill Unit 2, GSU purchased a 2250 HP ASD for Willow Glen, Unit 1. They relocated the control valve to the discharge of the 1B pump. Since they already operated the unit in a sliding throttle mode, there were no sliding throttle considerations in the economics other than reduced valve maintenance.

ASD TECHNOLOGY

GSU selected the transformerless 6-pulse input, 6-pulse output modified load-commutated inverter type ASD as shown in Figure 4-1. For this type of ASD, the rectifier and inverter are identical, each using a 6-pulse thyristor bridge as shown in Figure 4-2. The rectifier is line-commutated and the inverter is load-commutated. A three-phase line-to-line connected capacitor is connected to the motor terminals. This provides magnetizing current for the induction motor and it filters the output current wave shape for the induction motor.

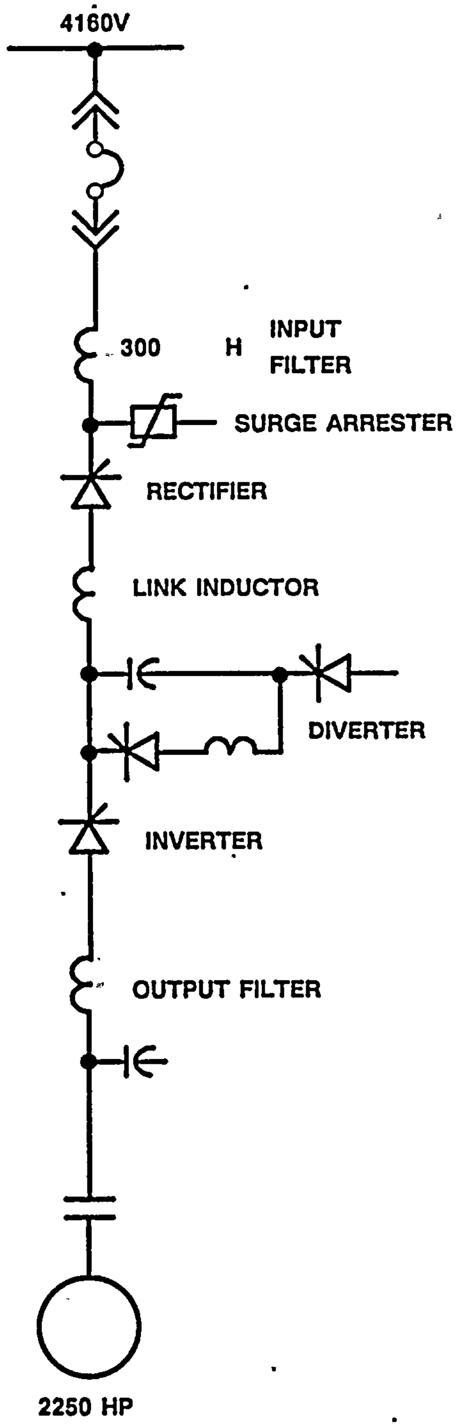


Figure 4-1

WILLOW GLEN PLANT, UNIT 1

6-PULSE MODIFIED LOAD-COMMUTATED TYPE ASD

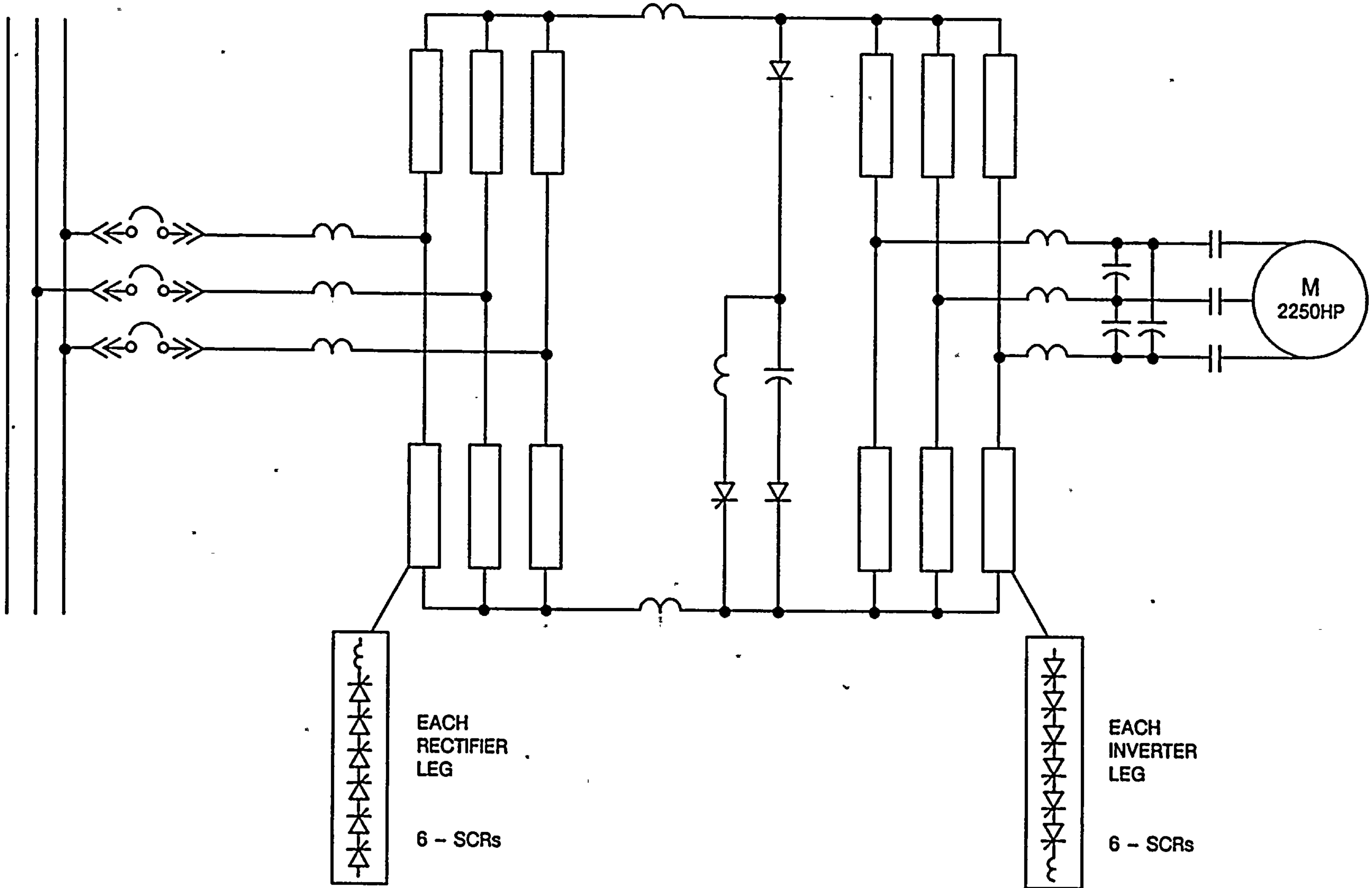


Figure 4-2

GULF STATES UTILITIES
WILLOW GLEN UNIT 1
MODIFIED LCI TYPE ASD FOR 2250HP BOILER FEED PUMP

As long as the output capacitor filter provides magnetizing current to the motor, the inverter is self-commutating from the motor internal voltage. As this mode of operation disappears near half of rated frequency (30 hz), the dc link diverter operates to commutate the inverter. The tank circuit, shown across the dc link in Figure 4-2 reverses the dc link voltage polarity when it is necessary to turn off the inverter thyristors that are conducting. By reversing the dc link voltage, voltage is removed from the inverter circuit and it stops conducting. The inverter circuit of another phase then starts to conduct and when it needs to be turned off the diverter again operates. This system of commutation continues until the frequency is increased to the point that the motor internal voltage again will commutate the inverter.

The ASD was located on a mezzanine floor between the basement and the turbine room, near the 4 kv switchgear. An isometric view is shown in Figure 4-3.

OPERATING EXPERIENCE

The GSU Willow Glen Plant, Unit 1, Boiler Feed Pump ASD has been in service since January 1986. They have experienced three failures of capacitors in the output filter which shut down the ASD. All capacitors were replaced in this case and GSU, as a precaution, has used a fan to cool the capacitors on hot days. No further failures have resulted and the ASD has performed well otherwise.

Figure 4-4 shows the input and output wave shapes of this system at 58 hz operation of the motor and Figure 4-5 shows Fourier Analysis of these waves. The input current shows the typical 6-pulse pattern. The output current has been smoothed by the output capacitor filter. The wave shapes are shown for an output frequency of 35 hz in Figure 4-6. The distortion was apparently caused by an increase in the fifth harmonic component of current as the output capacitor and motor winding inductance became resonant around 35 hz.

The heavy fifth harmonic current seen at 35 hz does not seem to cause torsional resonance problems with low inertia pumps such as this boiler feed pump. These currents have reportedly resulted in heavy shaft vibration in motors driving high inertia fans. A discussion of torsional vibration translating into lateral vibration can be found in Reference 9.

After the completion of the testing at Willow Glen, the manufacturer of this ASD has determined that an ungrounded inverter can allow a neutral shift on the motor 6 times per cycle resulting in increased levels of voltage to ground on the motor.

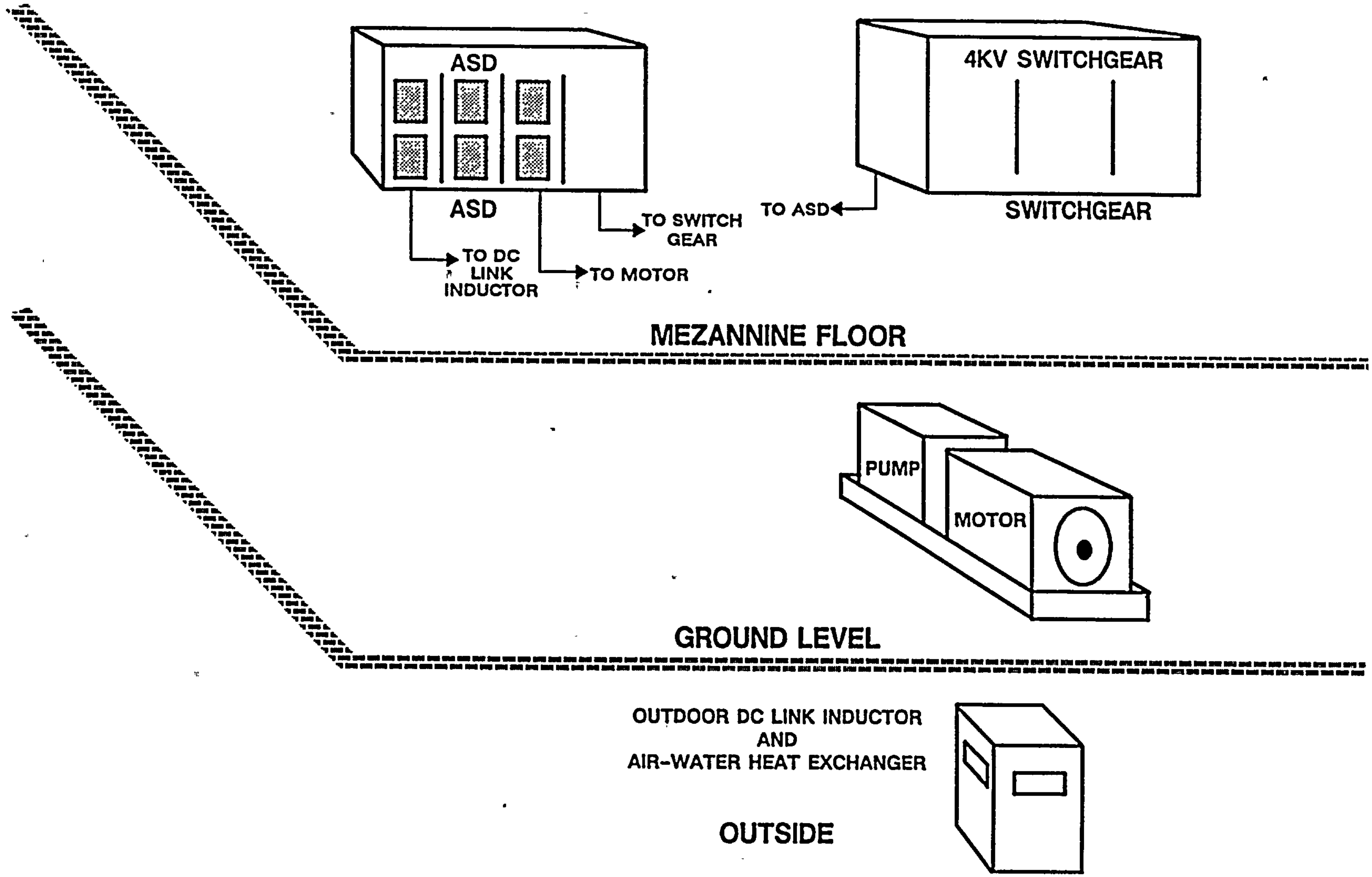


Figure 4-3
WILLOW GLEN UNIT 1
ISOMETRIC VIEW ASD INSTALLATION

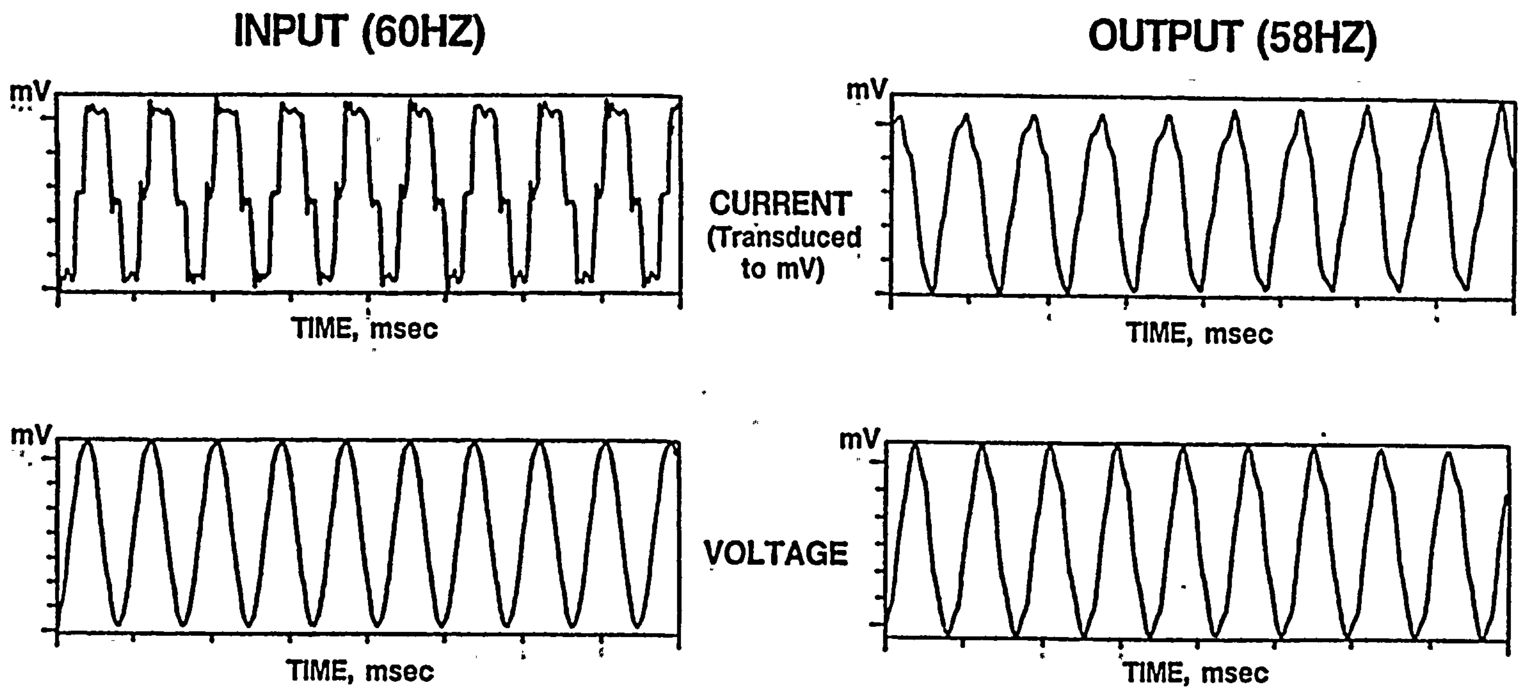


Figure 4-4
MODIFIED LOAD COMMUTATED TYPE ASD
6-PULSE INPUT, 6-PULSE OUTPUT

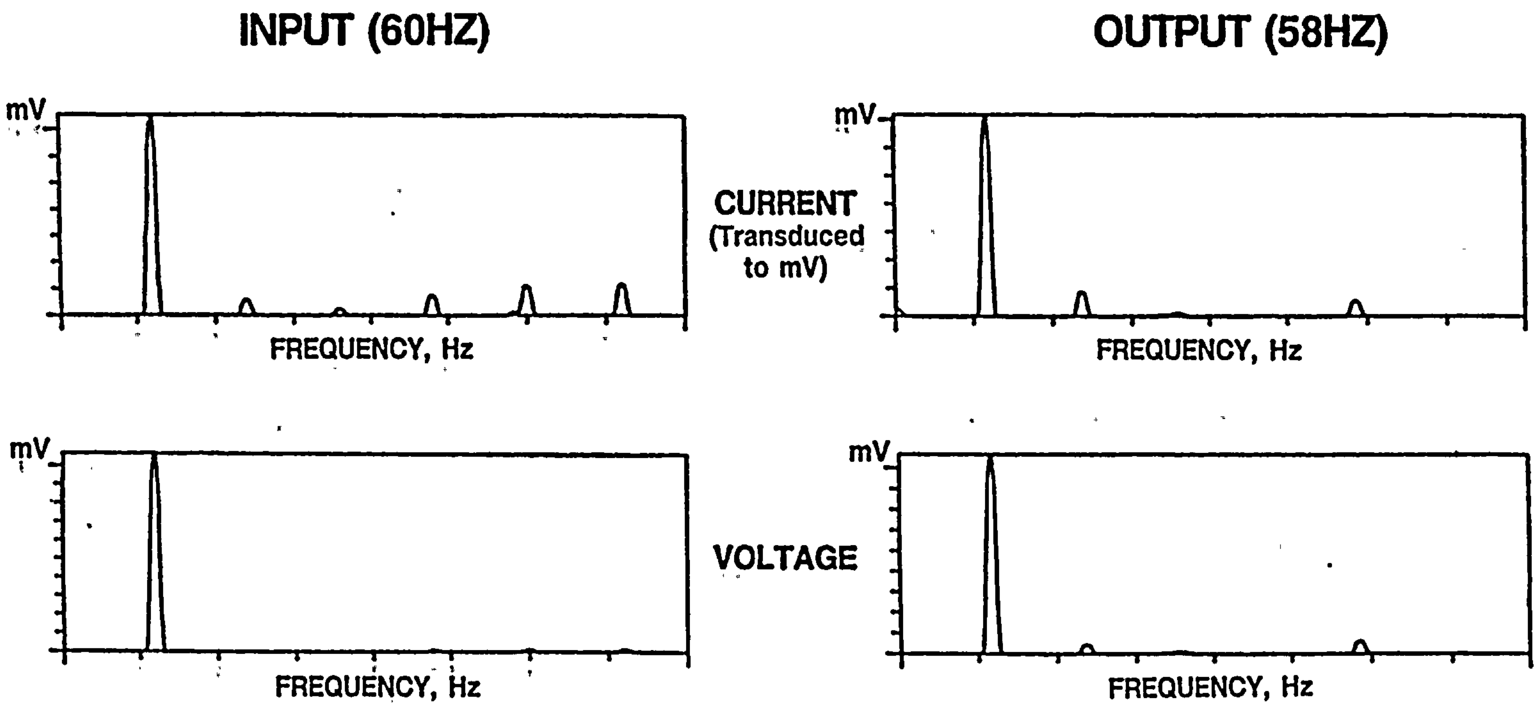


Figure 4-5
MODIFIED LCI TYPE ASD
6-PULSE INPUT, 6-PULSE OUTPUT
FOURIER ANALYSIS OF INPUT AND OUTPUT

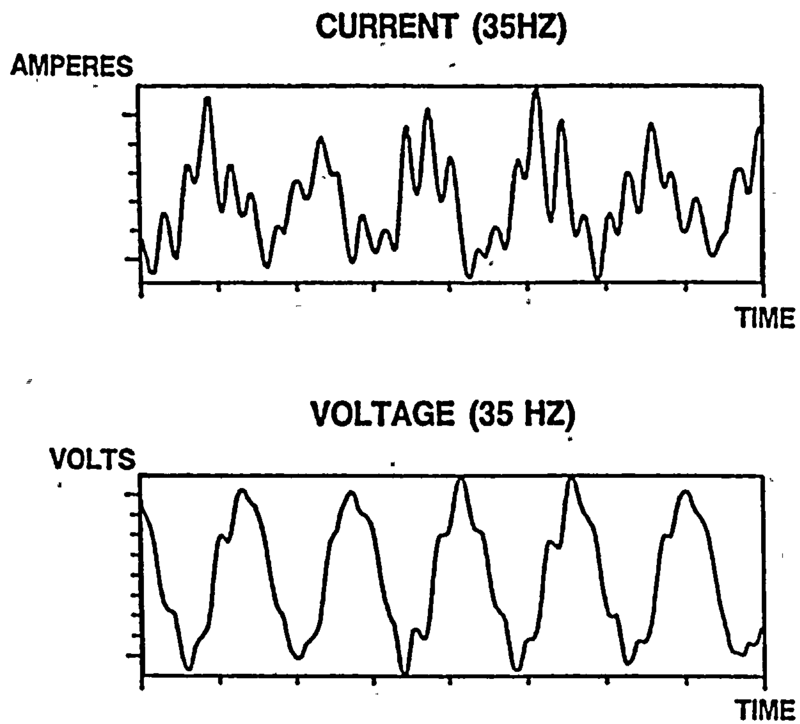


Figure 4-6
6-PULSE MODIFIED LCI ASD
INVERTER OUTPUT

Although there were no motor problems at Willow Glen related to the ASD application, this common mode voltage has resulted in some motor failures and needs to be considered. The result of 5 years of experience is that: (1) a ground is established near the motor and (2) input transformers are now used on all large ASDs to absorb the common mode voltage effect. These two adjustments, together, have had a positive impact on overall system reliability.

The test results of measurements taken at Willow Glen Plant in February 1986 are listed in Table 4-1.

RESULTS OF RETROFIT

The ASD installation at Willow Glen has achieved goals set by Gulf States Utilities. They have had reliable operation of the boiler feed pump with ASD control and estimate the annual savings at $130,000.

Table 4-1

WILLOW GLEN PLANT, UNIT 2
BOILER FEED PUMP
FIELD RESULTS

UNIT MW	HP	MOTOR FREQ.	RPM	% EXTRA MOTOR LOSS	HARMONICS				ASD EFF
					INPUT		OUTPUT		
					THD-V	THD-I	THD-V	THD-I	
115	2099	58	3451	.6	2.05	24.8	7.8	14.46	.92
80	1313	50	2915	1.5	1.49	25.7	10.32	25.6	.92
40	821	44	2618	2.6	.99	26.6	12.06	38.1	.91
15	361	35	2083	7.3	.70	35.3	16.86	67.1	.91

5. Oklahoma Gas & Electric Company
Seminole Plant
Unit 1, FD Fans
2-5000 HP ASD Field Test

Section 5

OKLAHOMA GAS & ELECTRIC COMPANY, SEMINOLE PLANT
UNIT 1, FD FANS, 2-5000 HP ASD FIELD TEST

UNIT DESCRIPTION

Seminole Unit 1 is a 530 MW gas and oil fired unit located at Konawa, Oklahoma. It is the first of a 3-unit plant and was installed in 1972.

PURPOSE OF PROJECT

Oklahoma Gas & Electric Company's decision to install a 5000 HP ASD on each of the 2-4000 HP FD Fans at Seminole Plant, Unit 1 was based on the following benefits:

- Annual fuel cost savings of $423,000 for improved operational efficiency at part load.
- Increased fan flow and unit output during peak demand periods during summer months. The Unit 1 FD Fans appeared to be short of capacity during hot weather and it was hoped that slightly overspeeding the fans with the ASDs would improve fan performance.
- Evaluation of operating experience with ASDs for further use in power plants at OG&E.

DESCRIPTION OF APPLICATION

The ASDs were furnished in a factory prefabricated house complete with air conditioning. The redundant 30 ton air conditioners were provided with economizer cooling units that allow the use of filtered outside air during much of the year when the outside air temperature is below 85°F.

The ASD house as shown in Figure 5-1 (isometric view) is located near the fan motors so that additional cable, conduit and cable tray were minimal. The existing motor cable was terminated in a new splice box near the motor. From the splice box, cables were extended to the isolation and bypass switches, the transformers and to the ASDs. The control system modification consists of using the existing vane control signal to control motor speed.

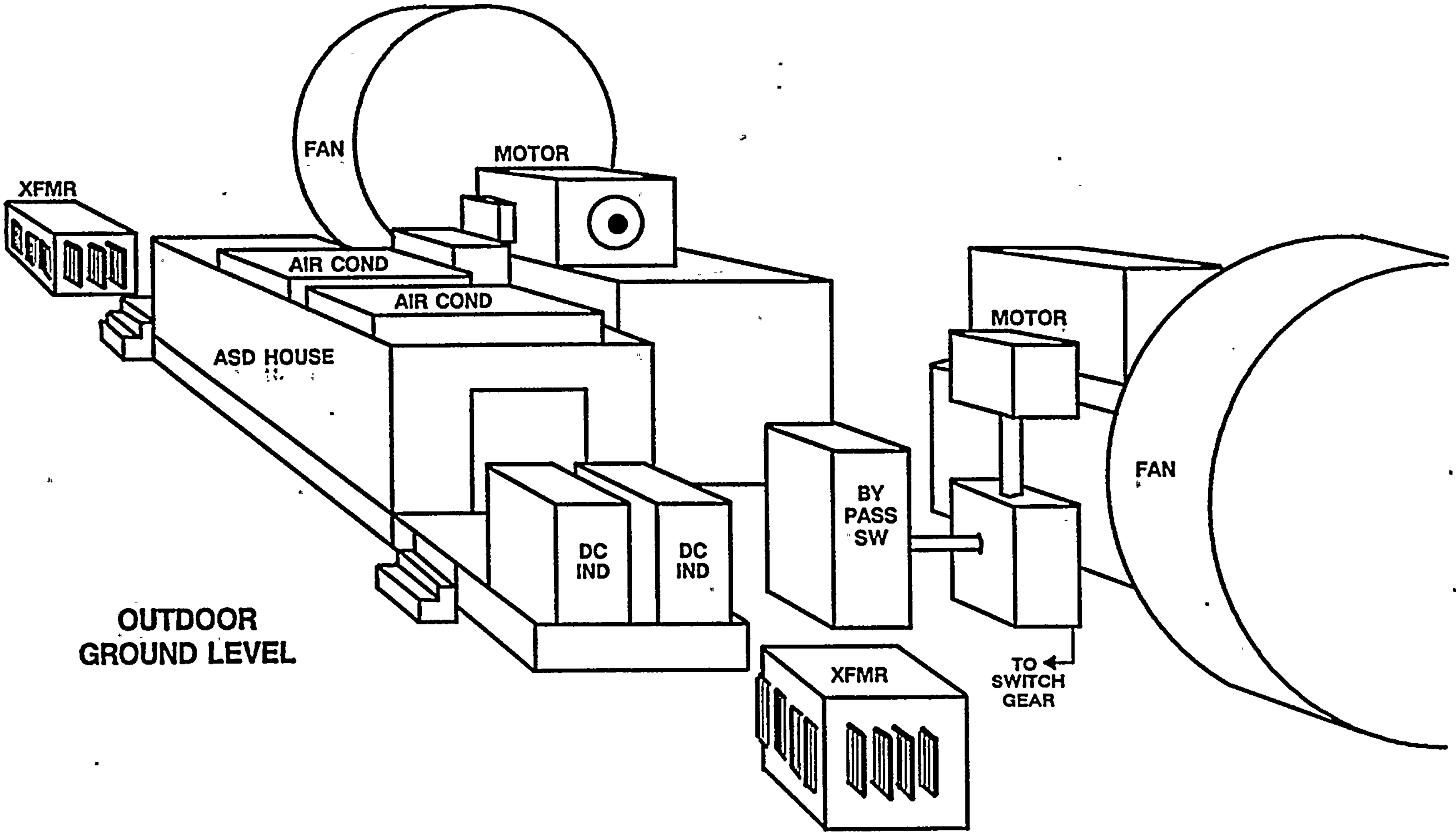


Figure 5-1
SEMINOLE UNIT 1
FORCED DRAFT FAN ASDs ISOMETRIC VIEW

ASD TECHNOLOGY

Each current source GTO-PWM ASD has a 12-pulse input type rectifier with isolation transformer, a dc link inductor, a 6-pulse current-source GTO-PWM inverter and an output capacitor filter as shown in Figure 5-2. This system, with the 12-pulse rectifier, has the potential for low input voltage and current harmonics. The output capacitor filter reduces the output harmonics that could cause motor heating. There is no resonance between the output filter and the motor because of output harmonic control with the GTO inverter's ability to remove harmonics that could cause resonance. Control and diagnostics are by digital microprocessor type technology. The power circuit for these ASDs is shown in Figure 5-3.

The capacitor, in parallel with the motor leakage inductance, creates an L-C circuit with a finite resonant frequency typically near 150 hz.

% Speed	Fundamental Frequency	Harmonic	Harmonic Frequency
19	11.5	13	150
23	13.6	11	150
36	21.4	7	150
50	30.0	5	150

The harmonic component at 150 hz will excite the LC circuit of the capacitor and the motor leakage reactance and allow a high circulating current at 150 hz. Since the resonant circuit is relatively undamped, the harmonic current can be amplified five to ten times.

The high harmonic currents flowing in the stator winding can cause motor shaft, frame, and coupling fatigue problems, if not controlled.

With the GTO inverter it is possible to eliminate selected harmonics that can excite the electrical resonance. Thus, the 11th and 13th harmonics are eliminated by notching at low speeds, the 7th and 11th are eliminated at higher speeds, the 7th and 5th at yet higher speed. Above 35 hz there is no further notching.

FIELD MEASUREMENTS

Tests on the ASDs at Seminole Plant were carried out in the period June 11-14, 1988. The FD Fans were operated with the ASDs controlling air flow by motor speed

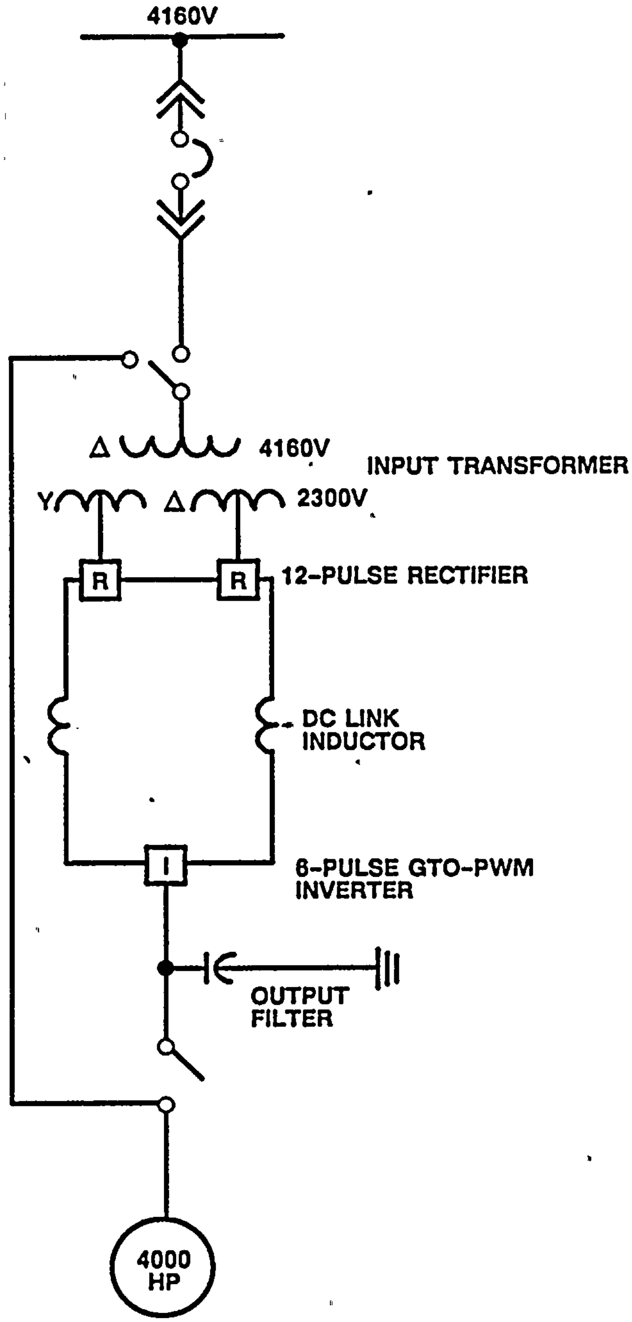


Figure 5-2
OKLAHOMA GAS & ELECTRIC CO.
5000 FD FAN ASD

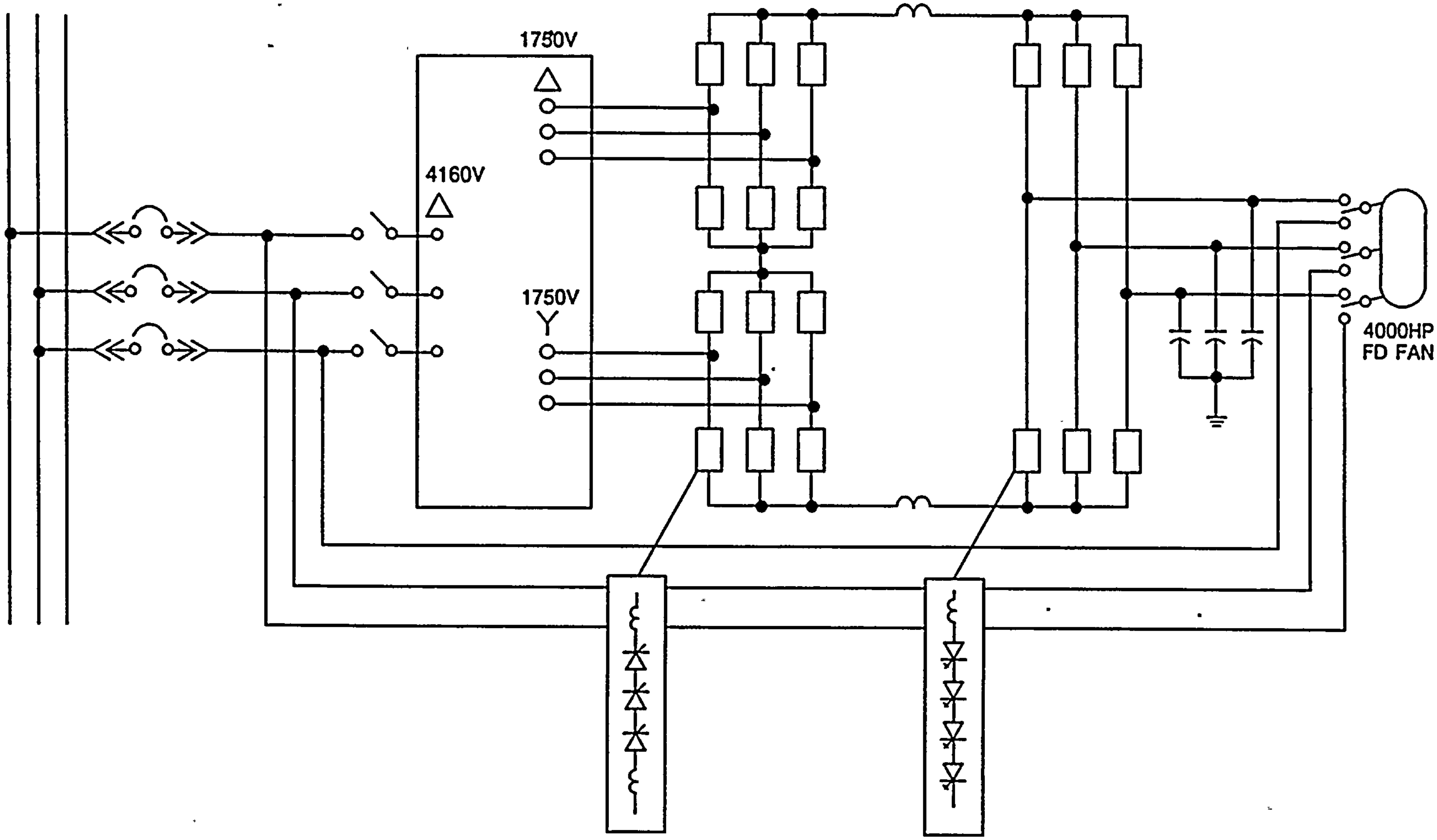


Figure 5-3
OKLAHOMA GAS & ELECTRIC
SEMINOLE UNIT 1
CURRENT SOURCE GTO-PWM TYPE ASD FOR 4600HP FD FAN MOTOR

and with the ASDs by-passed with air flow controlled by the inlet vanes. Tests were conducted at the following Unit 1 gross outputs:

400 MW
300 MW
250 MW
150 MW

It was not possible to operate at higher MW loads because of restrictions on the boiler.

The calculated and tested motor horsepower were as shown in Figure 5-4. Surprisingly, the motor horsepower was about 1000 HP higher than calculated, both with vane control and with ASDs. Tests were conducted on the same day on ASD control and on vane control at a series of load points. The difference in horsepower between vane control and ASD control had the general shape as predicted, but the difference or power savings was less than calculated.

The calculated kw savings and tested kw savings are as follows at the test points:

MW	Calculated Total Savings 2 Fans	Tested Total Savings 2-Fans
400	1670	792
300	2060	1287
250	1083	1970
150	1366	400

ANALYSIS OF TEST RESULTS

A study was undertaken to determine the cause of the difference in power required by the motors as determined by test and by calculation and to understand the reason for the reduced power savings between calculation and test.

The input data for the calculation was reviewed. The principal inputs that effect the horsepower calculations are as follows:

- fan curve - fan capacity vs fan head
- fan curve - fan capacity vs fan brake horsepower

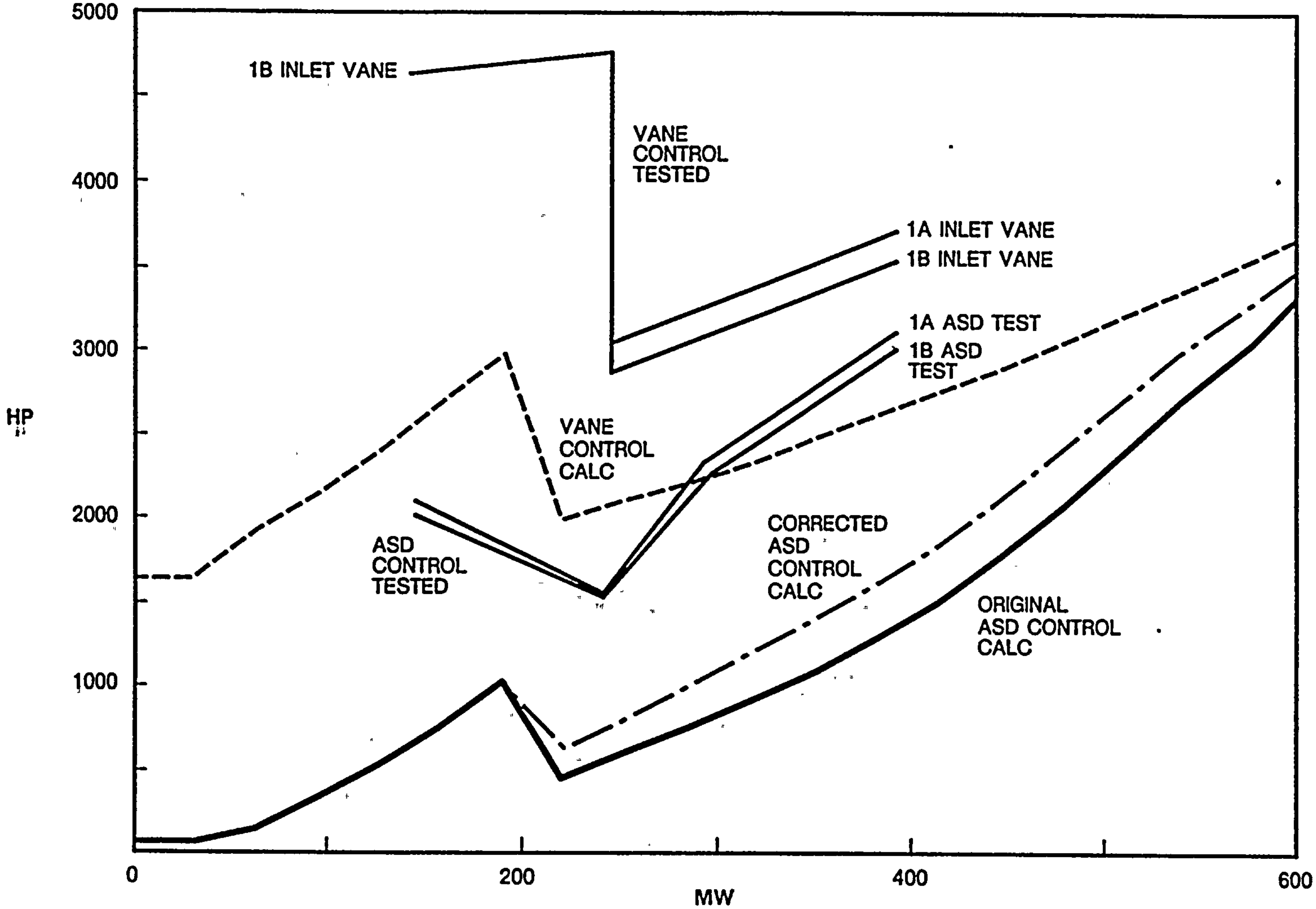


Figure 5-4

SEMINOLE PLANT - UNIT 1 FD FAN

TEST RESULTS

- system resistance - flow vs system head
- power output vs fan flow

After evaluation of the input data, the calculation method and information available at OG&E, and discussion with the fan manufacturer four problems were identified:

- The power output (MW) vs fan flow data for the calculation was not correct since it was based on too little excess air. Unit 1 at Seminole is operated with a high percentage of excess air. 27% excess air is used at full load and 60% at light loads. The calculation was based on a range of 5% to 30%. There was concern that the high excess air resulted in about 1000 HP extra per fan over the load range as compared to the calculated horsepower.
- The computer program, ASCON II, when used for fans did not differentiate between the two bhp curves supplied by the fan manufacturer. One curve is for operation on inlet vane control and the other is for operation with vanes wide open. Both curves should be used in the calculation of horsepower, the V.W.O curve for ASD operation and the vaned curve for vane control operation. The two fan horsepower curves for the Seminole Unit 2 fans are shown in Figure 5-5. The error introduced in the Seminole calculation made the dollar savings about 13% optimistic and the horsepower per fan on ASD operation was about 300 HP more than calculated.
- The fan manufacturer advised that the FD Fans at Seminole, Unit 1, did not meet their guarantees for flow and pressure. Subsequently, wedges were added to the fan blades to increase the pressure. Their best estimate is that in using the fan curve, the pressure is correct but the flow is 5% low. The bhp curves should be about correct.
- Air-preheater seals have a high leakage rate at Seminole Unit 1 at low load. This does not appear as excess air (air in excess of that needed to burn fuel), but as extra fan load.

Effects of these factors on the kw savings are shown in Figure 5-6.

To prevent the computational error, the ASCON II program was revised to allow the two brake horsepower curves to be used for fan calculations. Also, a caution was added to the ASCON II instruction book concerning the importance of fan flow vs MW input accuracy with regard to percent excess air and air leakage at the preheater. This is one of the key inputs to the calculation and is more sensitive to errors affecting the results than many of the other inputs.

The high excess air at Seminole results from the burner control system being setup to keep air registers open when burners are shutoff. There are 15 pairs of burners. Usually five burner pairs are shutoff at low loads. NFPA requires that

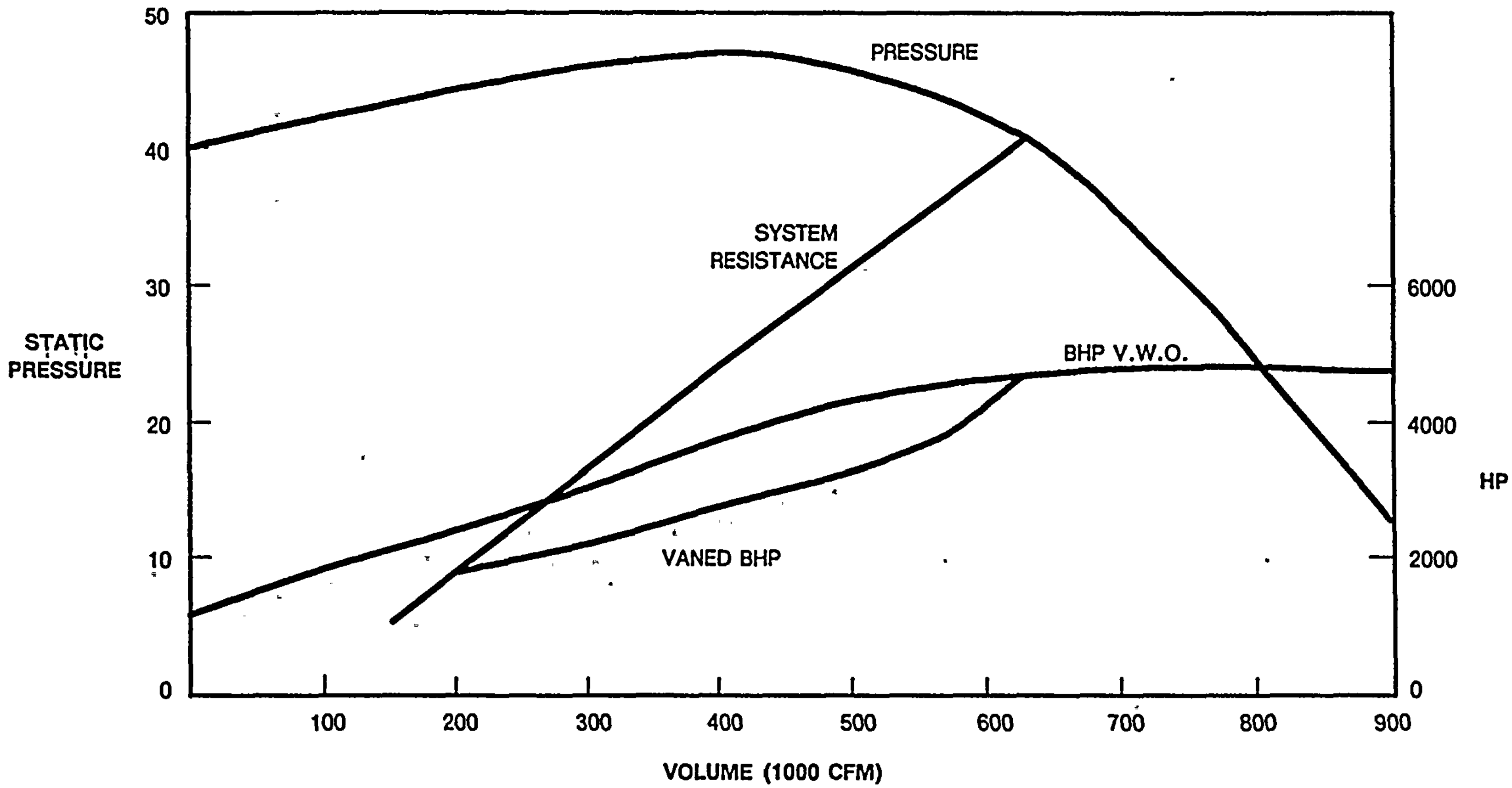


Figure 5-5

SEMINOLE PLANT - UNIT 1
FD FAN CURVES

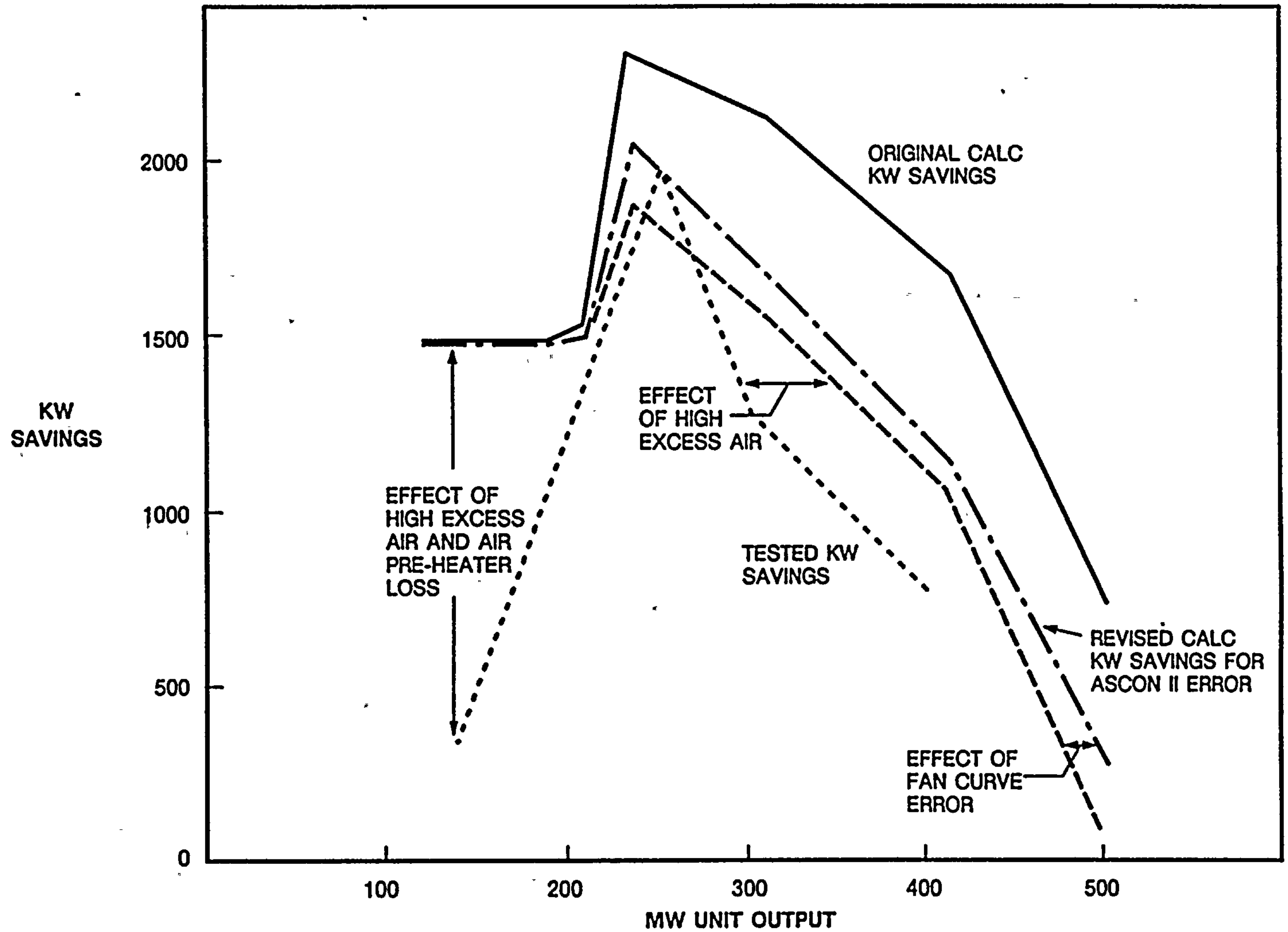


Figure 5-6

SEMINOLE PLANT - UNIT 1

CALCULATED AND TESTED KW SAVINGS

total air flow not be reduced below 25% of full load flow at minimum load, but registers can be closed on unused burners.

At reduced loads, it was estimated that operation with unused dampers closed would improve boiler performance by better utilizing excess air for fuel burning and steam temperature control.

OG&E modified their operation to close registers not in use and repaired the air preheater leak. The low load economics produced by the ASDs did not materially improve. It appears that the air preheater seal design is such that there is a high air loss at low load. When operating one fan at light load without the ASD, the fan operates with the inlet vanes nearly open at rated HP. When this is compared to operation with two fans on ASD control (for this condition the inlet vanes are wide open), the horsepower used is nearly the same. Thus, it appears that the air preheater seal design dominates the air requirement at light load and the ASD economics at low load are not as good as anticipated.

HARMONICS AND THD

Current and voltage wave shapes for the 12-pulse input 6-pulse output GTO-PWM ASD, along with the Fourier analysis, are shown in Figures 5-7 and 5-8. The total harmonic distortion determined for the 4 kV bus and for the ASD output by the tests are shown in Table 5-1 for the operating speed range.

The THD (voltage) was specified at the 4 kV bus in the purchase specification not to exceed 3.3%. Since the measured value is in the order of 5.3%, the ASD manufacturer is evaluating the necessary modifications to bring the harmonic level within expectations.

In Table 5-2, the principal voltage harmonics injected to the 4 kV bus are listed in percent of the fundamental by order of harmonic. With the 12-pulse rectifier system, the 5th and 7th harmonics are at low levels as will be seen in Figure 5-8.

The harmonics of Table 5-2 were also seen in the 480 volt and 110 volt busses. Harmonic increases caused by the ASDs at the generator and generator neutral were negligible.

The ASD produced harmonics have affected the operation of the boiler controls. The burner controls and drum level were affected. Some improvement was obtained by installing a constant voltage transformer with harmonic filter on the bus

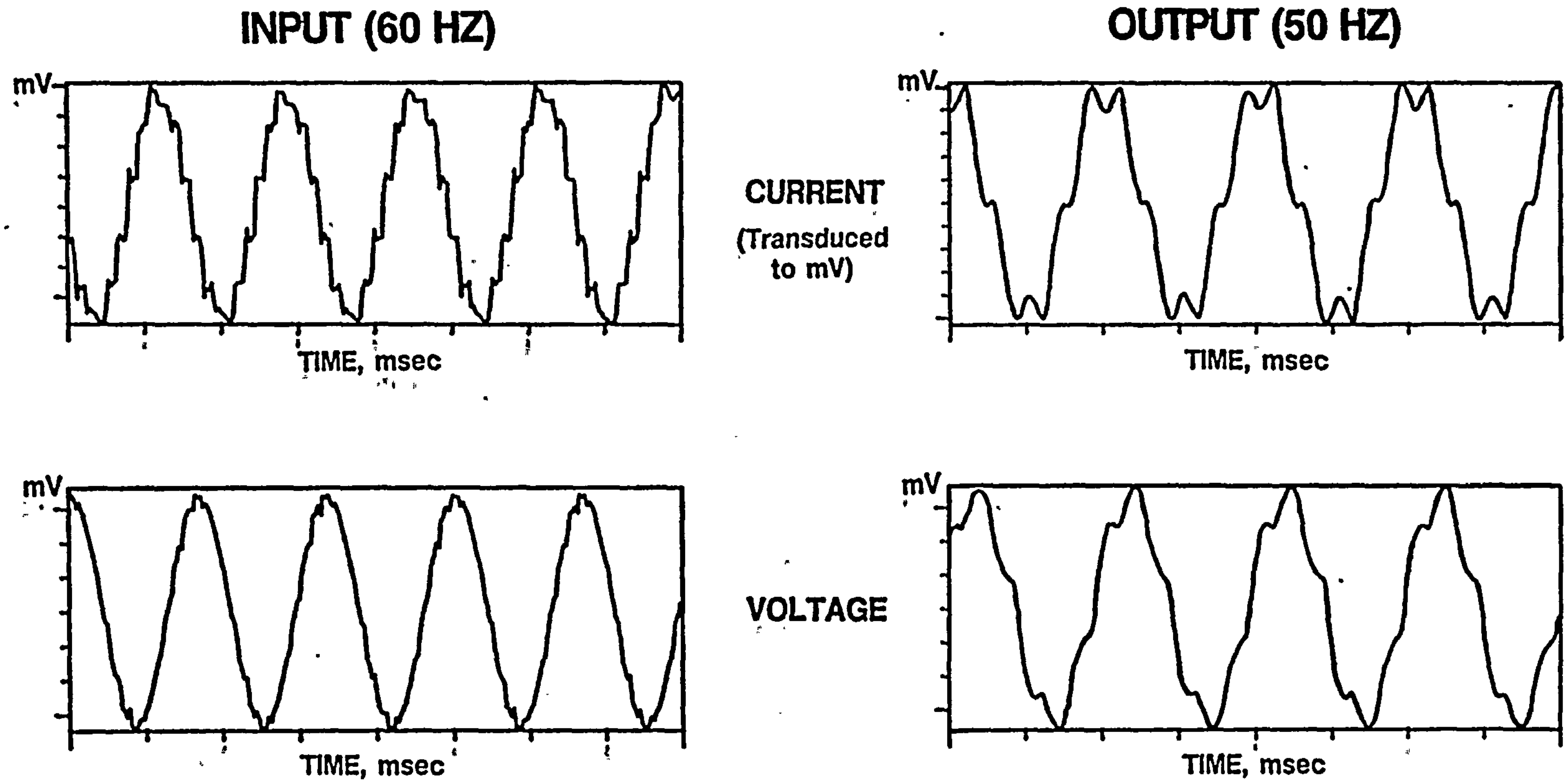


Figure 5-7
OKLAHOMA GAS & ELECTRIC
CURRENT SOURCE GTO - PWM ASD

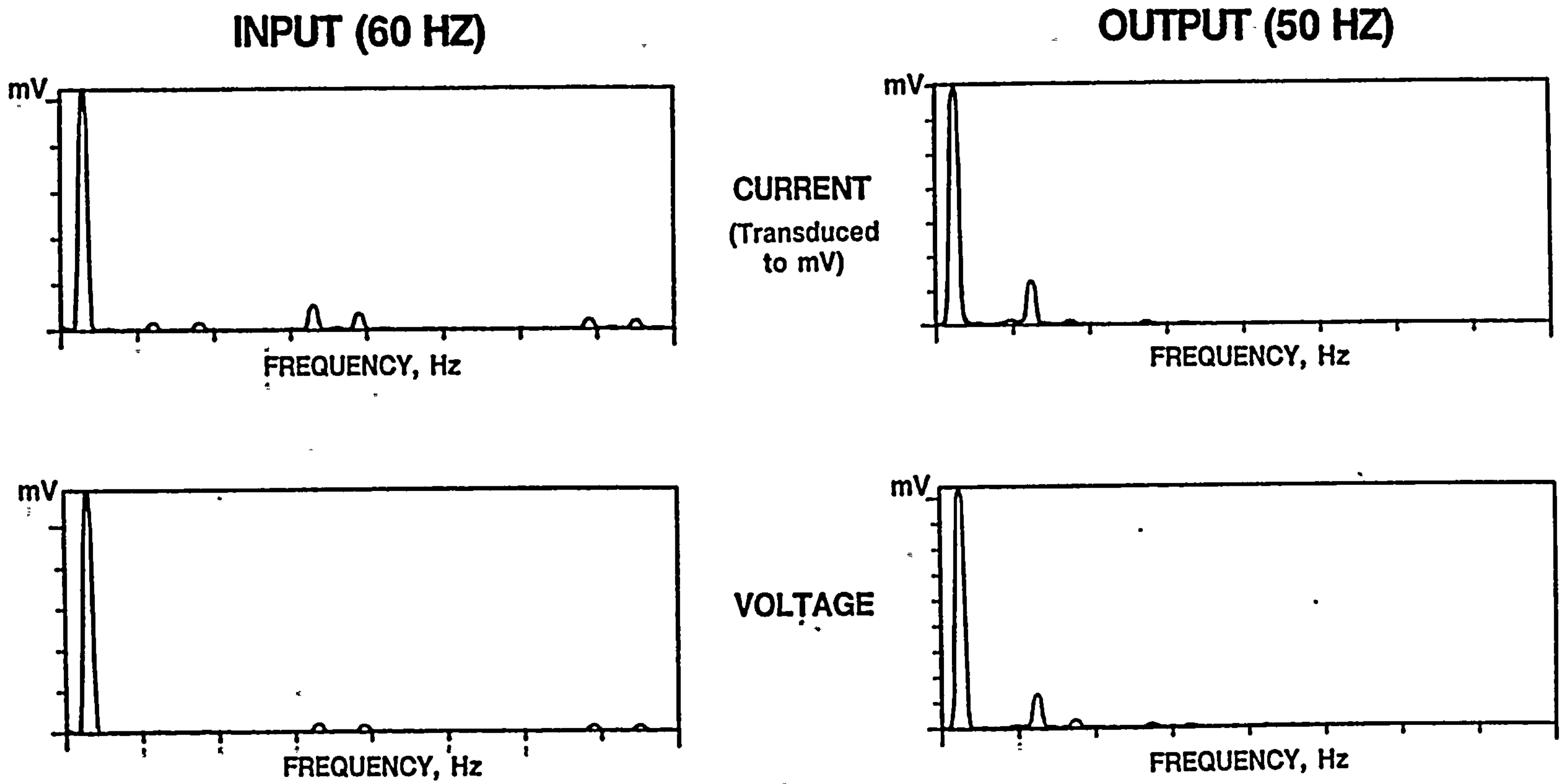


Figure 5-8

OKLAHOMA GAS & ELECTRIC
CURRENT SOURCE GTO - PWM ASD
FOURIER ANALYSIS OF INPUT AND OUTPUT

Table 5-1

SEMINOLE, UNIT 1 FD FANS
FIELD RESULTS

IA FAN					HARMONICS, PERCENT				
					INPUT		OUTPUT		
UNIT MW	HP	MOTOR FREQ.	RPM	% EXTRA MOTOR LOSS	THD-V	THD-I	THD-V	THD-I	ASD EFF
400	2713	50	741	1.7	5.16	13.7	13.9	17.6	.943
300	2030	43.75	649	0.4	5.10	14.7	8.0	8.6	.938
250	1371	40	593	1.24	4.7	16.3	12.6	15.6	.928
150	1853	43.75	649	0.5	5.3	14.9	8.8	9.6	.916

IB FAN					HARMONICS, PERCENT				
					INPUT		OUTPUT		
UNIT MW	HP	MOTOR FREQ.	RPM	% EXTRA MOTOR LOSS	THD-V	THD-I	THD-V	THD-I	ASD EFF
400	2621	49.00	726	1.8	5.3	14.1	8.6	18.9	.956
300	1980	43.75	649	0.3	5.2	14.8	8.2	8.34	.929
250	1382	39.00	579	1.4	4.5	16.7	14.1	17.4	.942
150	1732	43	638	0.6	4.5	12.8	8.8	10.1	.949

Table 5-2

SEMINOLE PLANT

VOLTAGE HARMONICS INJECTED BY ASDs TO 4kV BUS, PERCENT

	1A ASD INPUT				1B ASD INPUT			
	HARMONIC ORDER							
MW	11	13	23	25	11	13	23	25
150	3.4	2.3	2.4	2.1	3.2	2.2	2.3	2.1
250	3.0	1.9	2.3	1.9	2.9	1.8	2.3	1.9
300	3.1	2.2	2.5	2.3	2.9	2.3	2.5	2.3
400	3.2	2.5	2.2	2.2	3.3	2.5	2.2	2.1

feeding these controls but there has still been some erratic operation of these control systems. It is anticipated that with the reduction of THD to 3% or less, these control problems will be eliminated.

PERFORMANCE OF THE GTO-PWM CURRENT SOURCE INVERTER

The GTO-PWM inverters experienced a number of failures in their first six months of operation. These failures were related to problems with the chopper power supply. These problems were resolved in December, 1987, and these inverters have performed with a high degree of reliability. Fortunately, the ASDs were provided with manual by-pass switches and the ASD failures did not result in a significant loss of generation. These repeated failures did, however, cause a lack of confidence in the ASDs on the part of the plant operators. Even though the ASDs have performed reliably for over a year now, the plant operators have some concern about loss of fans because of thyristor failure.

VIBRATION MEASUREMENT

Vibration at the motor and fan bearings was recorded at each test point. Vibration recorded at all speeds was within acceptable loads. Some high frequency local resonance at the motor bearings was detected at 660 rpm on the 1A fan and at 750 rpm on the 1B fan, but the amplitude of vibration was low. These vibrations may be caused by inverter harmonics exciting resonance frequency in the stator core since the vibrations are not present with the motor operating without the ASDs.

NOISE MEASUREMENT

Noise data trended lower as the rpm of the fan decreased. The A-weighted level dropped from 90 db at 880 rpm to 84 db at 660 rpm. Since the decibel system that is used in sound measurement is a logarithmic scale, a 3 db reduction is significant. This is a 50% reduction in noise and an even greater reduction of perceived noise in terms of human ear response. Noise reductions at lower speed were difficult to document because of ambient power plant noise and noise reflections from adjacent buildings.

ASD EFFICIENCY

ASD efficiency at 400 MW gross generation was measured to be in the range of 96 to 97% without the air conditioning. With the air conditioning, it was calculated to be 94 to 96%.

RESULTS OF RETROFIT

Annual savings of $231,000 per year were estimated by OG&E engineers. An additional improvement of $98,000 was obtained from repairing leakage at the air preheater. The preheater seal design is such that there is a high air requirement at low loads. Thus, it is possible to operate with one fully loaded fan with vanes wide open at light load. This horsepower is about the same as is used when operating two fans with ASDs at reduced speed also with vanes wide open. Because of this air preheater characteristic the fuel cost savings were not as high as originally anticipated.

Changes in annual load duration curve and a reduction in fuel cost had negative impact on the fuel cost savings, but the major effect was the loss of air at the preheater seal at light load on the unit.

6. Iowa Public Service Company
George Neal Plant
Unit 2, Boiler Feed Pumps
2-6300 HP ASD Field Test

Section 6

IOWA PUBLIC SERVICE COMPANY, GEORGE NEAL PLANT
UNIT 2, BOILER FEED PUMPS, 2-6300 HP ASD FIELD TEST

UNIT DESCRIPTION

George Neal Plant, Unit 2 is a 320 MW coal fired unit located on the Missouri River south of Sioux City, Iowa. The unit went into service in 1972.

PURPOSE OF PROJECT

IPS decided to convert the 2-7000 HP boiler feed pumps on Unit 2 to adjustable speed operation for the following reasons:

- change the unit to sliding throttle operation to improve part load efficiency of the unit.
- improved part load efficiency of the unit would result in more operating hours for the unit in the MAPP power pool and increase revenues for IPS.

DESCRIPTION OF APPLICATION

Each 7000 HP boiler feed pump on Neal No. 2 is driven by 2-3500 HP, 3600 rpm motors connected in tandem. With the installation of the ASDs, a by-pass switch arrangement was provided so that the motors can be returned to original constant speed operation if there is serious ASD trouble. Prior to the installation of the ASDs, pump flow was controlled by a control valve. The control valve for each pump has been retained and becomes an integral part of the ASD control scheme. With the ASD controlling motor speed, constant boiler drum level is maintained by creating a differential pressure across the feedwater regulator. This 175 to 275 psi differential controls pump speed. Pump maximum flow and minimum flow limits under adjustable speed operation are monitored by the plant computer system.

ASD TECHNOLOGY

Each ASD has a modified LCI type inverter and is comprised of a three winding input transformer to provide for the 12-pulse input rectifier, a dc link inductor, a GTO link commutator circuit, a 6-pulse inverter with output L-C filter and a

mechanical by-pass switch arrangement. The one-line diagram for these ASDs is shown in Figure 6-1.

GTOs were used in the dc link commutator circuit to commutate the inverter thyristors at frequencies below 37 hz (2200 rpm). The dc link commutator GTOs are also used to eliminate frequencies that could cause resonance between the output filter and the motor. The electrical circuit is shown in Figure 6-2.

At Neal Unit 2 the 2-7000 HP boiler feed pump motors are located at ground level. The 4 kV switchgear is on the second floor of the plant. The ASD installation was located in available space on the third floor at the turbine room level. An isometric sketch is in Figure 6-3. Because of the 120°F temperature possible in the summer on the turbine room floor, the ASDs were located in a pre-engineered, insulated building that was assembled in 46-inch wide panels. This ASD building contained the ASDs, redundant air-to-water heat exchangers, filters and redundant blowers. The air cooling system uses turbine auxiliary cooling water and is shown schematically in Figure 6-4. The output filter and by-pass switches were located adjacent to the ASD house. The input transformers were located at ground level outside the plant. Cables that were added for the ASD installation were run in underground duct bank outside the plant and in cable bus elsewhere. At 4 kV, 3-500 million circular mil (MCM) and 4-500 MCM cables per phase were required for the currents.

OPERATING EXPERIENCE

Operation of these ASDs was delayed until January of 1988. A tornado extensively damaged the coal handling system of Unit 4 at Neal Plant in July 1987. This occurred before the ASD installation was complete on Unit 2 and Unit 2 ran at full load while repairs were made to Unit 4. After unit 4 repairs were complete, the Unit 2 ASD installation was finished and the ASDs were put into service in late 1987. These ASDs were among the first to use GTOs in the diverter circuit. Considerable field engineering was needed to make the ASDs work as originally conceived. There were application problems to be resolved with the GTO's in this link commutator circuit and it was not until January 1988 that the ASD control and firing circuits were appropriately modified.

Since January 1988 the ASDs have performed reliably, although there have been failures of thyristors (any failure is considered to be excessive). The failures occur at start-up of the ASD and the cause of failure is under study. With the (N+1) capability, the failures have not resulted in loss of the ASD. The

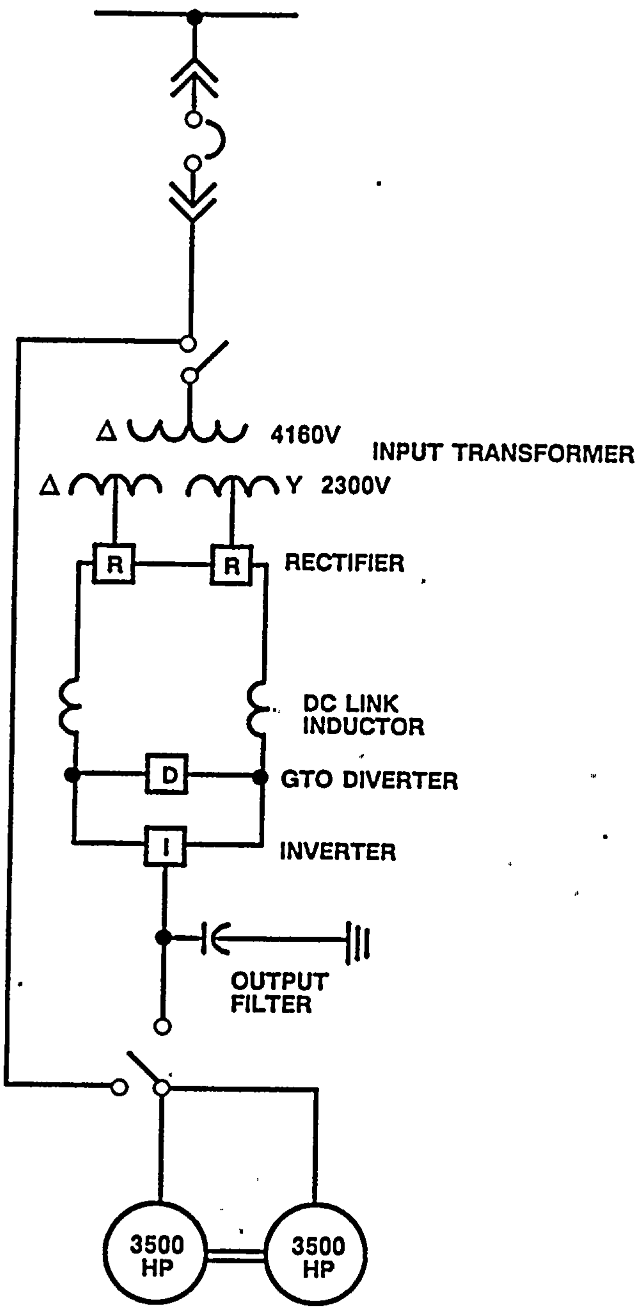


Figure 6-1

IOWA PUBLIC SERVICE CO.
GEORGE NEAL PLANT UNIT 2

BOILER FEEDPUMP
MODIFIED LCI TYPE ASD

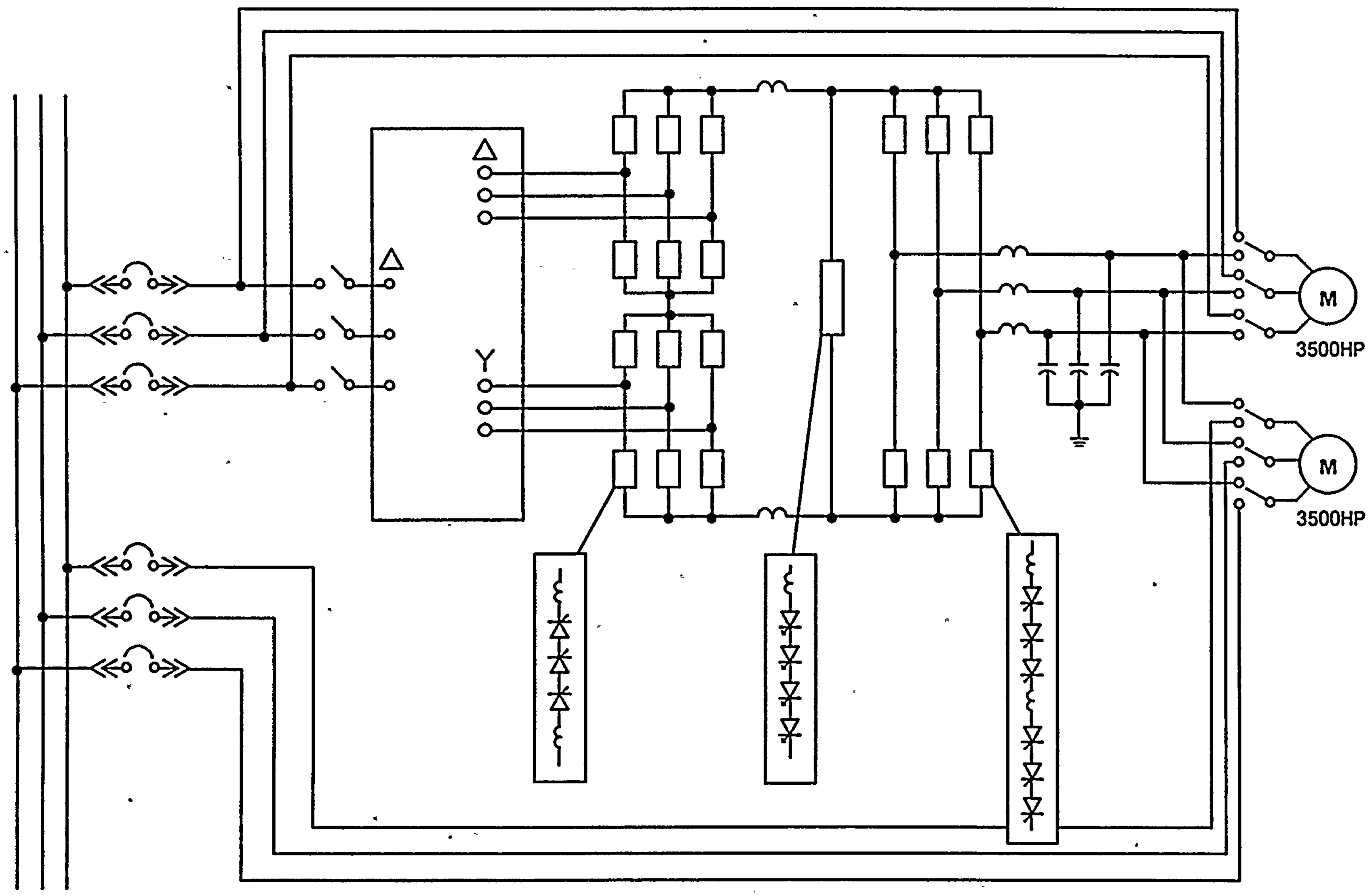


Figure 6-2
IOWA PUBLIC SERVICE
NEAL UNIT 2
MODIFIED LCI TYPE ASD FOR 7000HP BOILER FEED PUMP

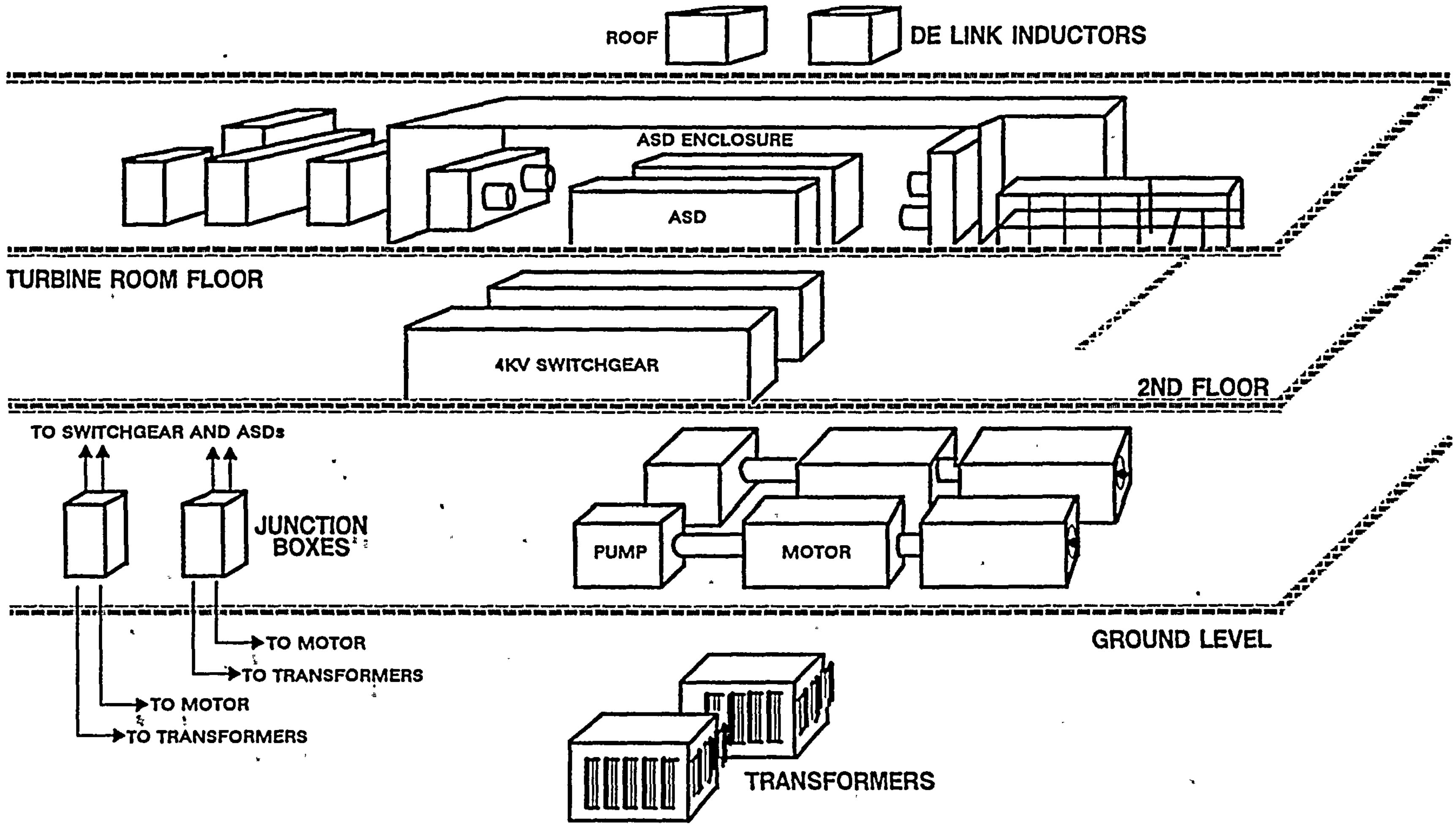


Figure 6-3
NEAL PLANT UNIT 2
ISOMETRIC VIEW ASD INSTALLATION

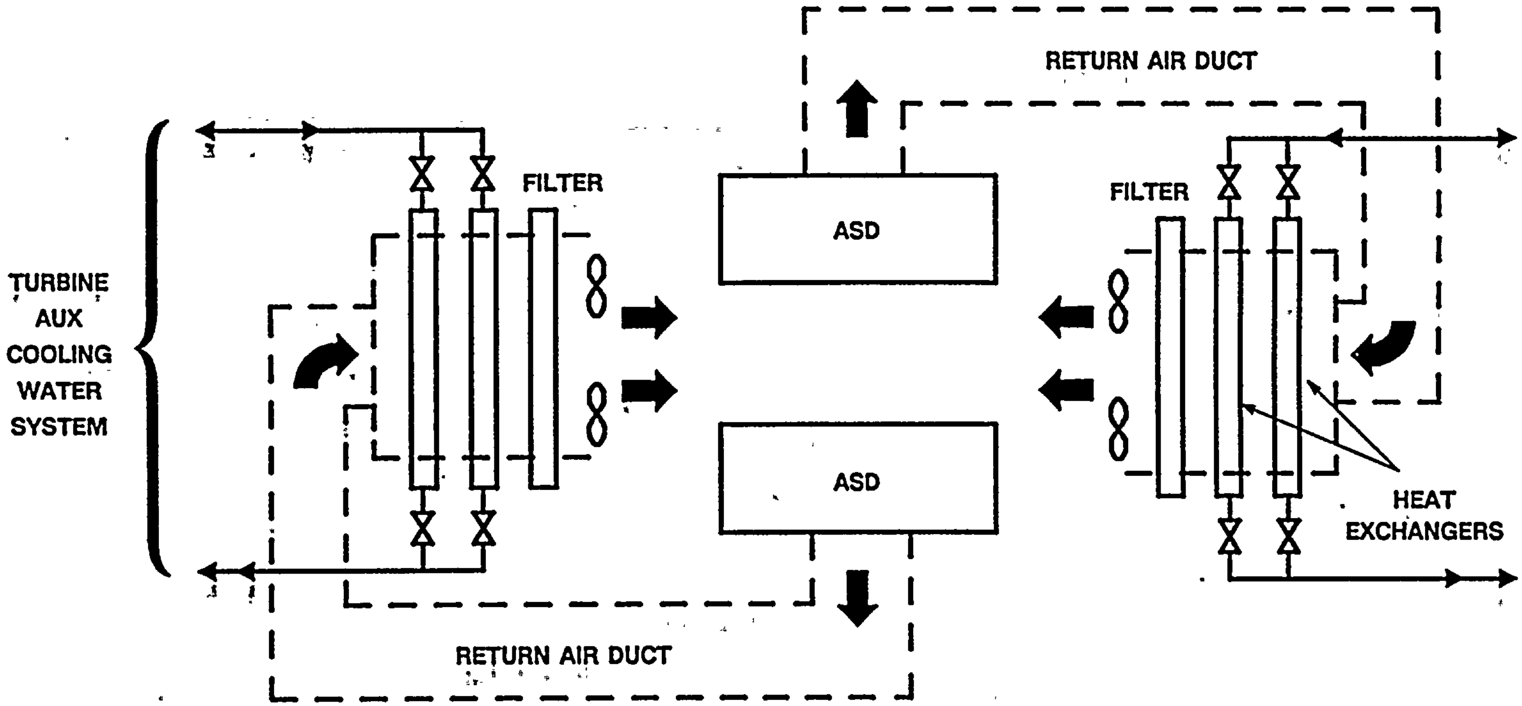


Figure 6-4
IOWA PUBLIC SERVICE - NEAL 2
AIR-COOLED ASDs

electrical by-pass switch arrangement allowed replacement of thyristors without shutdown of the unit. The (N+1) capability of ASDs is discussed in the Conclusions section, later in this report.

FIELD TESTS

Field Tests were conducted on April 4 and 5, 1989. Unit 2 was operated at three load levels, 90 MW, 180 MW and 270 MW. Measurements were made with the boiler feed pumps operating on ASD control and on fixed speed valve control at each MW level. Measurements were made at the PTs and CTs in the switchgear and at temporary PTs and CTs that were located at the output of the inverter between the output filter and the motors at the by-pass switch. With this arrangement, input power was measured at the primary side of the isolation transformer and at the ASD output past the filter. Thus, harmonics measured reflect the benefit of the input transformer and the output filter.

The test results are summarized in Figures 6-5 through 6-13. The use of motor speed to take advantage of reduced throttle pressure is shown in Figure 6-5. With automatic control and both pumps running, the speed range is 2234 to 3550 rpm.

Figure 6-6 shows the comparison of power to the boiler feed pumps with valve control and with ASD control. Figure 6-7 shows the savings. At 90 MW the savings is 1886 kw comparing one pump on valve control and two pumps on ASD control. Still comparing two pumps on ASD control with one on valve control at 180 MW, the savings drop to 118 kw, but when the second pump is turned on with valve control, the savings maximize at 3190 kw.

At full load, 290 MW, savings of 1276 kw was measured. IPS's own tests confirmed the savings at 290 MW to be more like 2.4 MW.

ASD losses appear to be higher than expected as shown in Figure 6-8. This was reflected by the inability of the ASD air cooling system to hold constant inlet air temperatures when the diverter circuit operated. The extra losses appear to be related to snubber losses in the GTO diverter. The snubber is a capacitor-resistor circuit that diverts current when the GTO thyristor turns off. When the GTO diverter circuit operates, the cooling air temperature increases and it has been necessary to operate both heat exchangers at all times.

Figure 6-9 shows Total Harmonic Distortion, current and voltage, at the input and output of the ASD. Input voltage distortion peaked at 3.6%. Output current

TEST	NET MW	RPM	BFP DISCH. PRESS.	THROTTLE PRESS.	MAIN STEAM TEMP	REHEAT STEAM TEMP
1	90	2234	1558	1078	996	943
2	180	2609	1996	1414	992	987
3	270	2979	2686	1951	985	989
4	90	3550				
5	180	3550	3819	2390	931	904
6	270	3550	3525	2397	987	1007

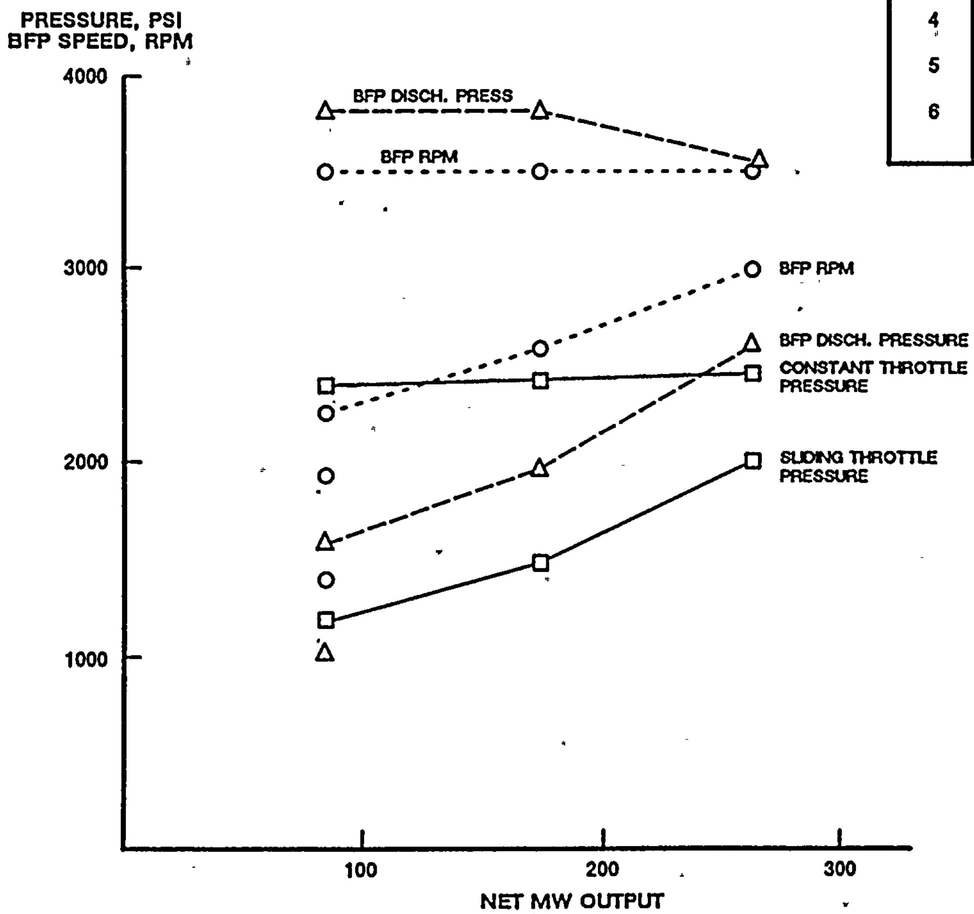


Figure 6-5

NEAL PLANT

BFP DISCHARGE PRESSURE AND THROTTLE PRESSURE FIXED SPEED AND ASD CONTROL OF BFP

TEST	NET MW	NO. OF PUMPS OPER.	CNTRL MODE	RPM	KW INPUT PER PP	KW OUTPUT PER PP	KW INPUT TOTAL
1	90	2 AUTO	ASD	2234	1048	1018	2096
2	180	2 MANUAL	ASD	2609	2053	1791	4106
3	270	2 MANUAL	ASD	2979	3206	3098	6412
4	90	1 MANUAL	VALVE	3550	3982		3982
5	180	1 MANUAL	VALVE	3550	4224		4224
5A	180	2 MANUAL	VALVE	3550	3648		7296
6	270	2 MANUAL	VALVE	3550	3844		7688

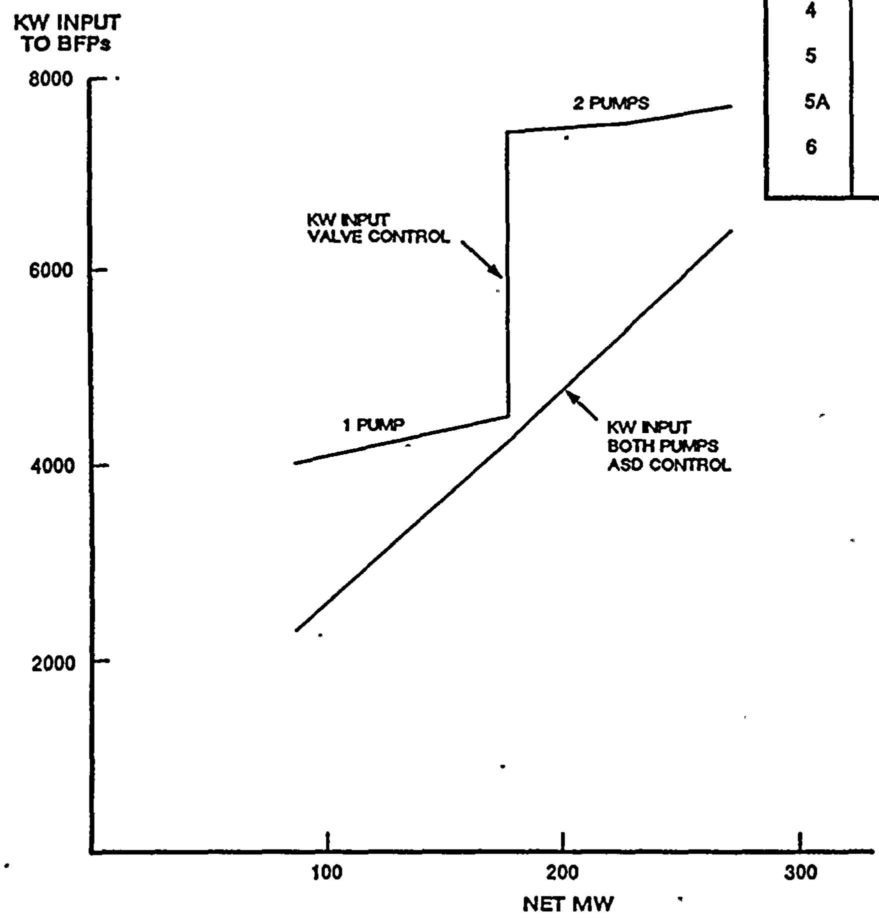


Figure 6-6

NEAL PLANT, UNIT 2

KW INPUT TO BOILER FEED PUMPS
ASD CONTROL AND VALVE CONTROL

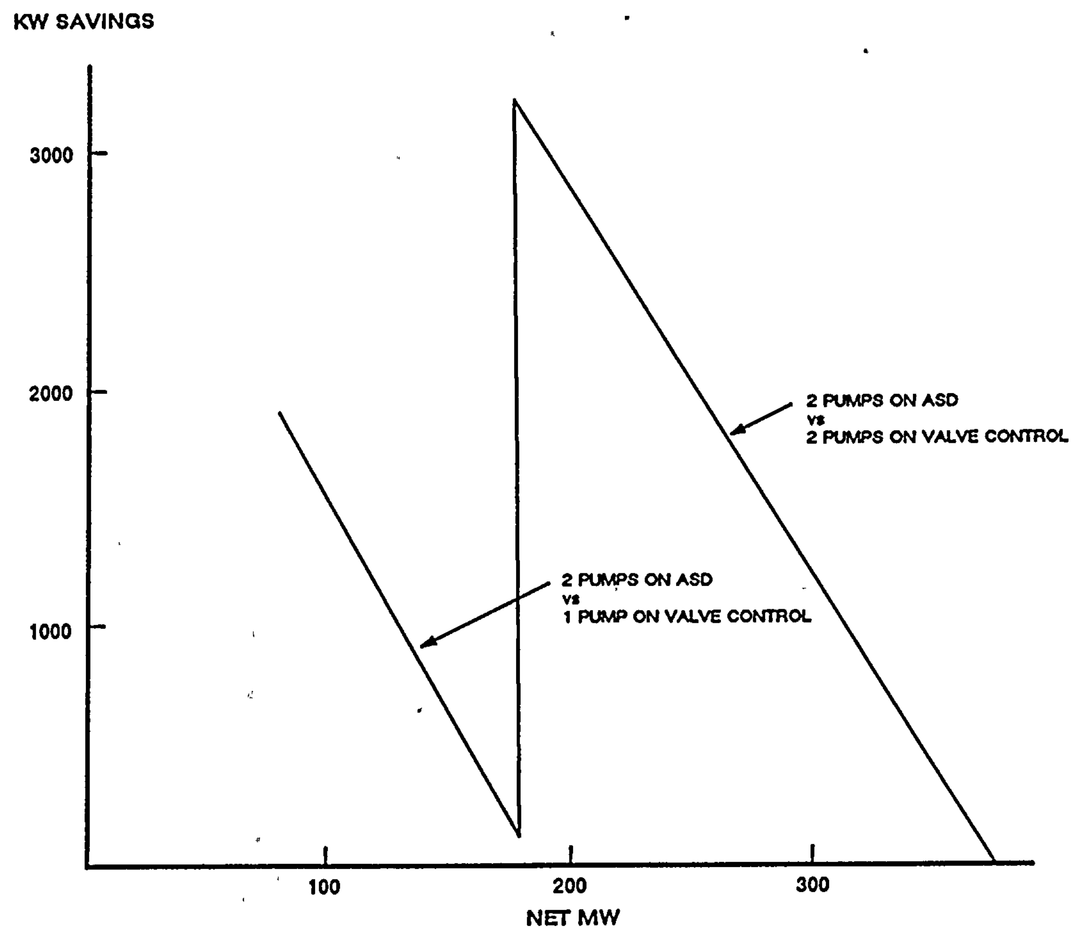


Figure 6-7

NEAL PLANT, UNIT 2

KW SAVINGS vs MW FOR ASD CONTROL OF BOILER FEED PUMPS

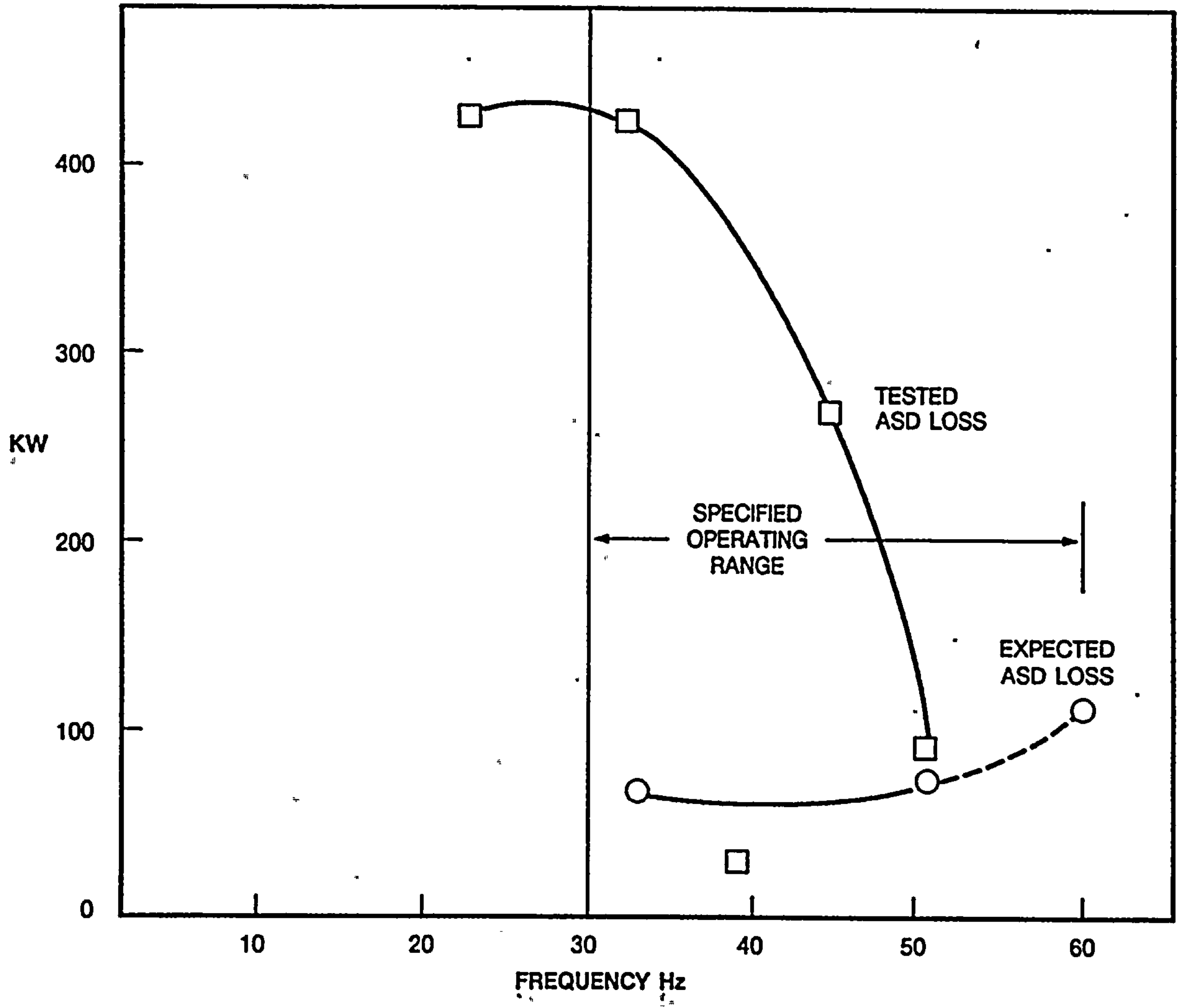


Figure 6-8
NEAL PLANT
TESTED AND EXPECTED ASD LOSSES
BOILER FEED PUMP ASD

TEST	NET MW	RPM	INPUT KW	THD INPUT		THD OUTPUT	
				V	I	V	I
1	90	2234	1048	2.67	23.9	9.8	28.5
2	180	2609	2053	2.88	18.0	7.6	8.8
3	270	2979	3206	3.60	17.3	11.2	11.2

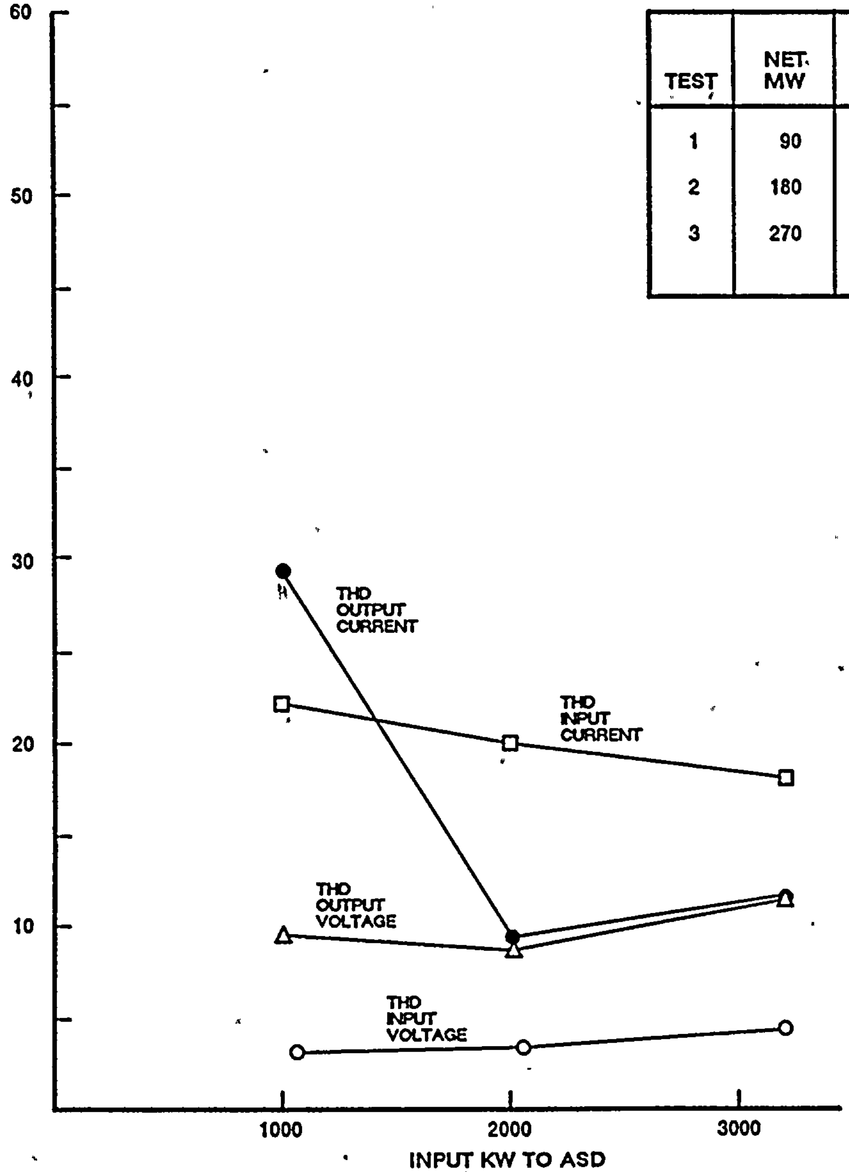


Figure 6-9
NEAL PLANT, UNIT 2
TOTAL HARMONIC DISTORTION

distortion for this ASD was high at light loads with diverter operation. At higher speeds with LCI operation of the inverter, output THD is normal, 11.2% voltage and 11.2% current distortion.

Figures 6-10 and 6-11 show wave shapes and Fourier analysis of wave shapes with the inverter operating at 50 hz. Figures 6-12 and 6-13 show similar outputs at 31.25 hz inverter operation. Figure 6-12 shows the presence of fifth harmonic current build up which results from resonance between the motor and the filter capacitor.

RESULTS OF THE RETROFIT

Iowa Public Service Company engineers evaluated the performance of the unit with sliding pressure operation with ASD control of the boiler feed pumps. Details of operation of the boiler with constant pressure and with variable pressure are listed in Table 6-1 for 120 MW net load. Drum pressure was reduced from 2452 psig to 1101 psig. Main steam pressure was reduced from 2442 psig to 1042 psig.

At the time these tests were made, the spray controls had not been optimized and there was some increase in boiler tube temperatures when operating with ASD control, but the temperatures were within design limits.

The fuel cost savings developed by IPS are shown in Figure 6-14 for the load range of the unit and the heat rate improvement is shown in Figure 6-15.

The fuel cost savings resulting from the use of ASDs and sliding pressure for 1988 and 1989 are significant and are listed in Table 6-2 for Unit 2 capacity factors of 46.61% for 1988 and 31.29% for 1989. Total savings through June of 1989 are estimated at $960,780. On an annualized basis savings are expected to be $347,707 with a fuel cost of $1.599/MBtu.

This full load auxiliary power savings was confirmed by Iowa Public Service Co. engineers to be about 2.4 MW. This 2.4 MW reduction translates to additional plant capacity. At $1200/kw installed cost for new generation, this additional capacity has a value of $2.88 million which is slightly more than the installed cost of the ASDs and pays for the ASD retrofit.

This additional capacity has been produced with no additional emissions from the plant and shows promise for ASD applications that will have the effect of reducing

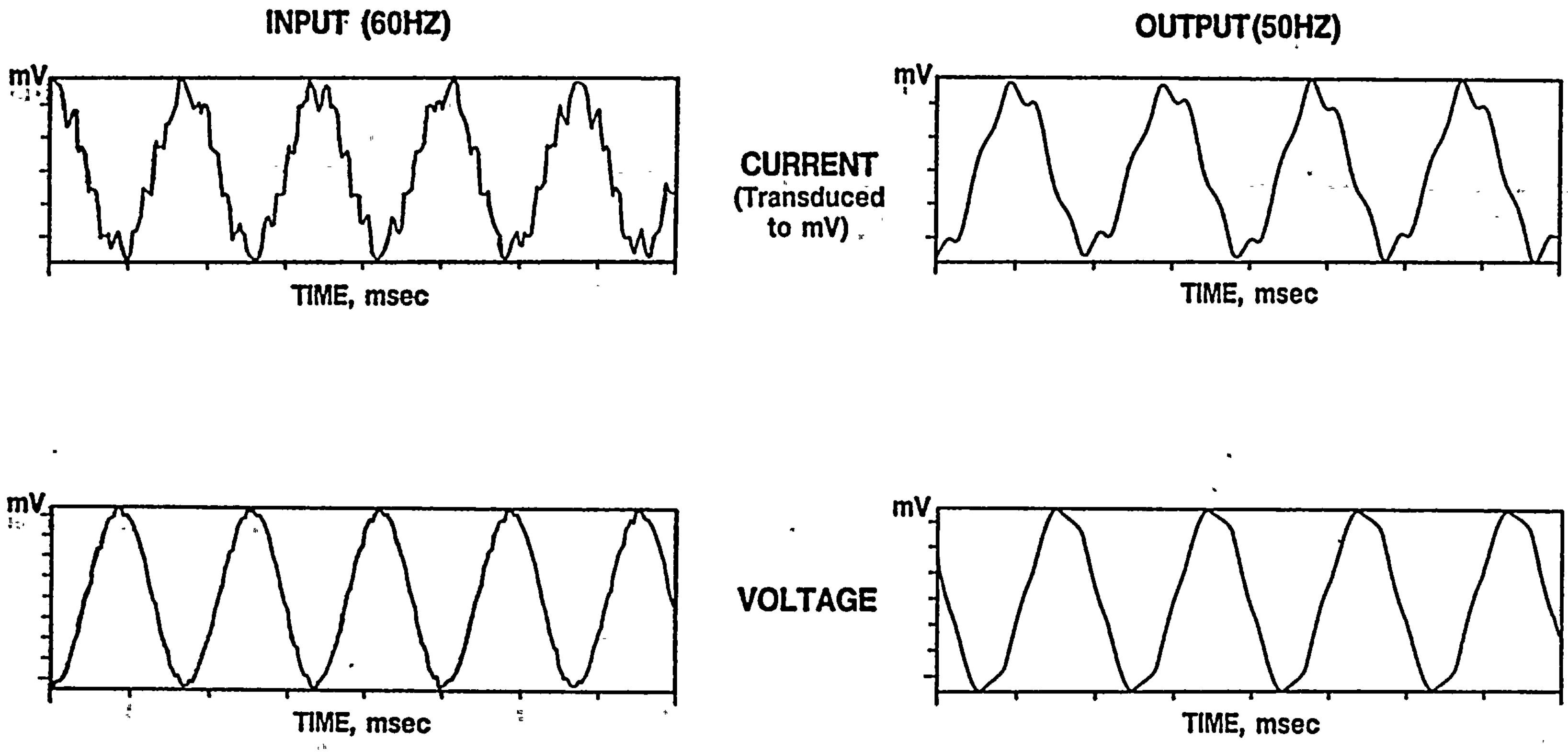


Figure 6-10
IOWA PUBLIC SERVICE COMPANY - NEAL PLANT
12-PUSLE INPUT, 6-PULSE OUTPUT
MODIFIED LCI ASD

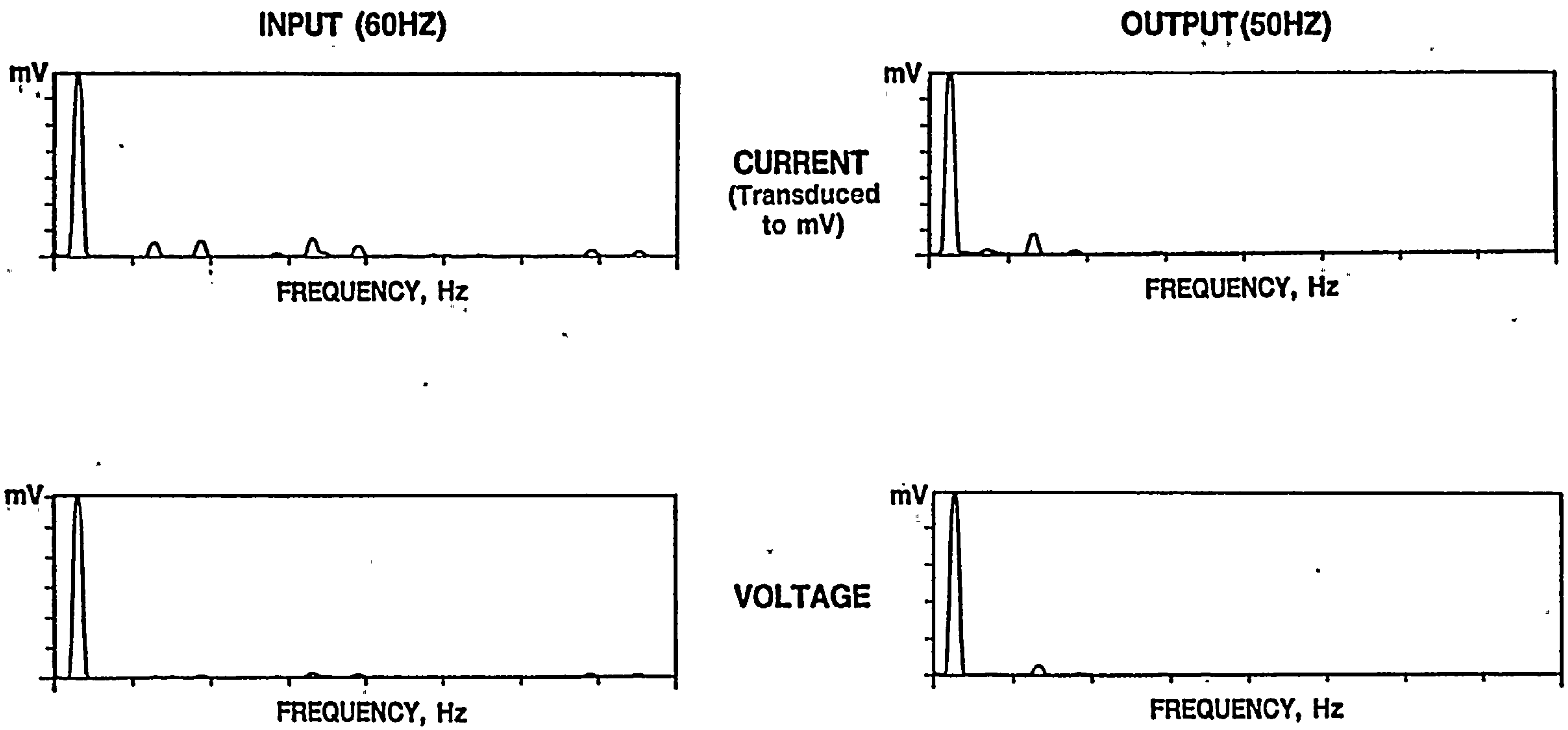


Figure 6-11
IOWA PUBLIC SERVICE COMPANY - NEAL PLANT
12-PULSE, 6-PULSE OUTPUT
MODIFIED LCI ASD

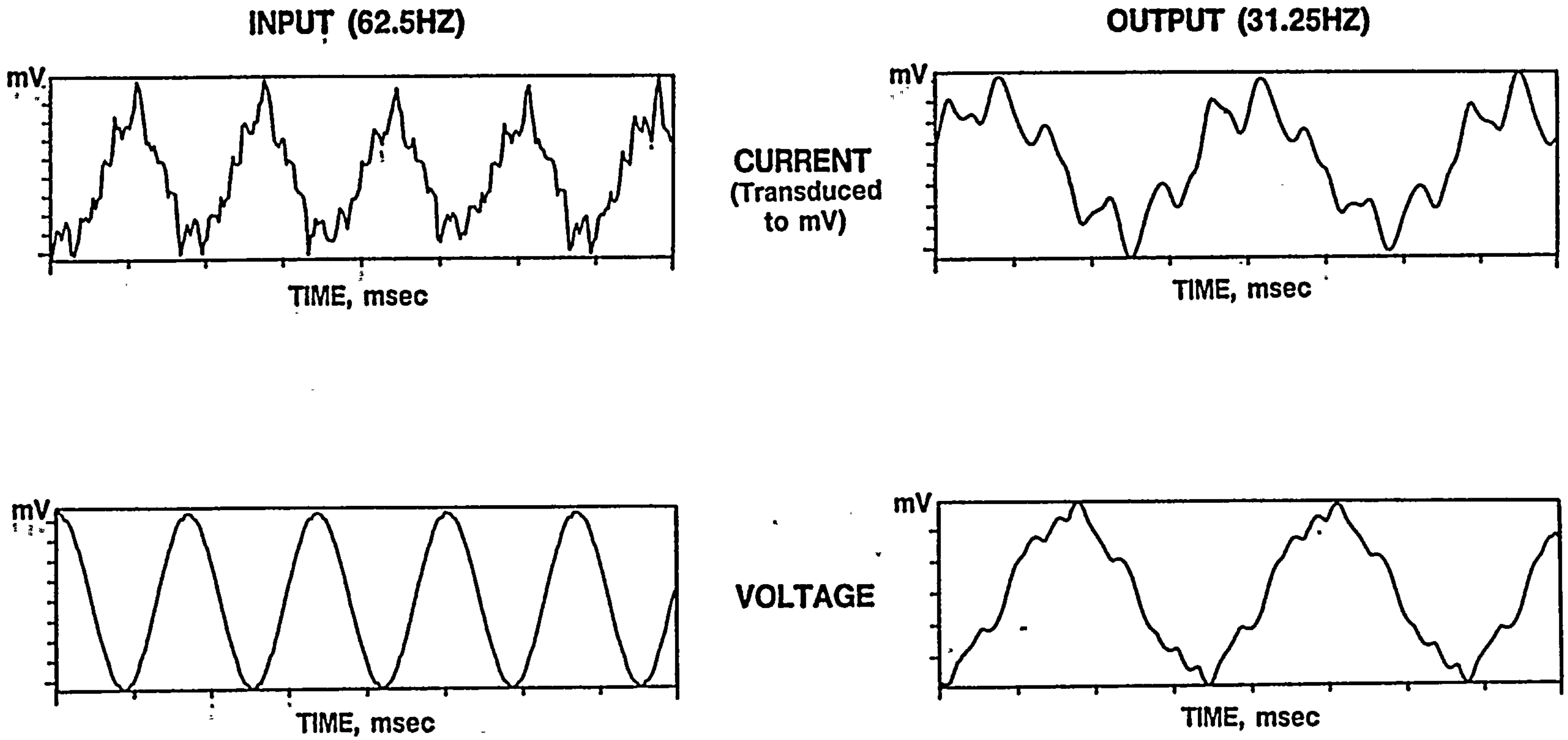


Figure 6-12
IOWA PUBLIC SERVICE COMPANY - NEAL PLANT
12-PULSE INPUT, 6-PULSE OUTPUT
MODIFIED LCI ASD

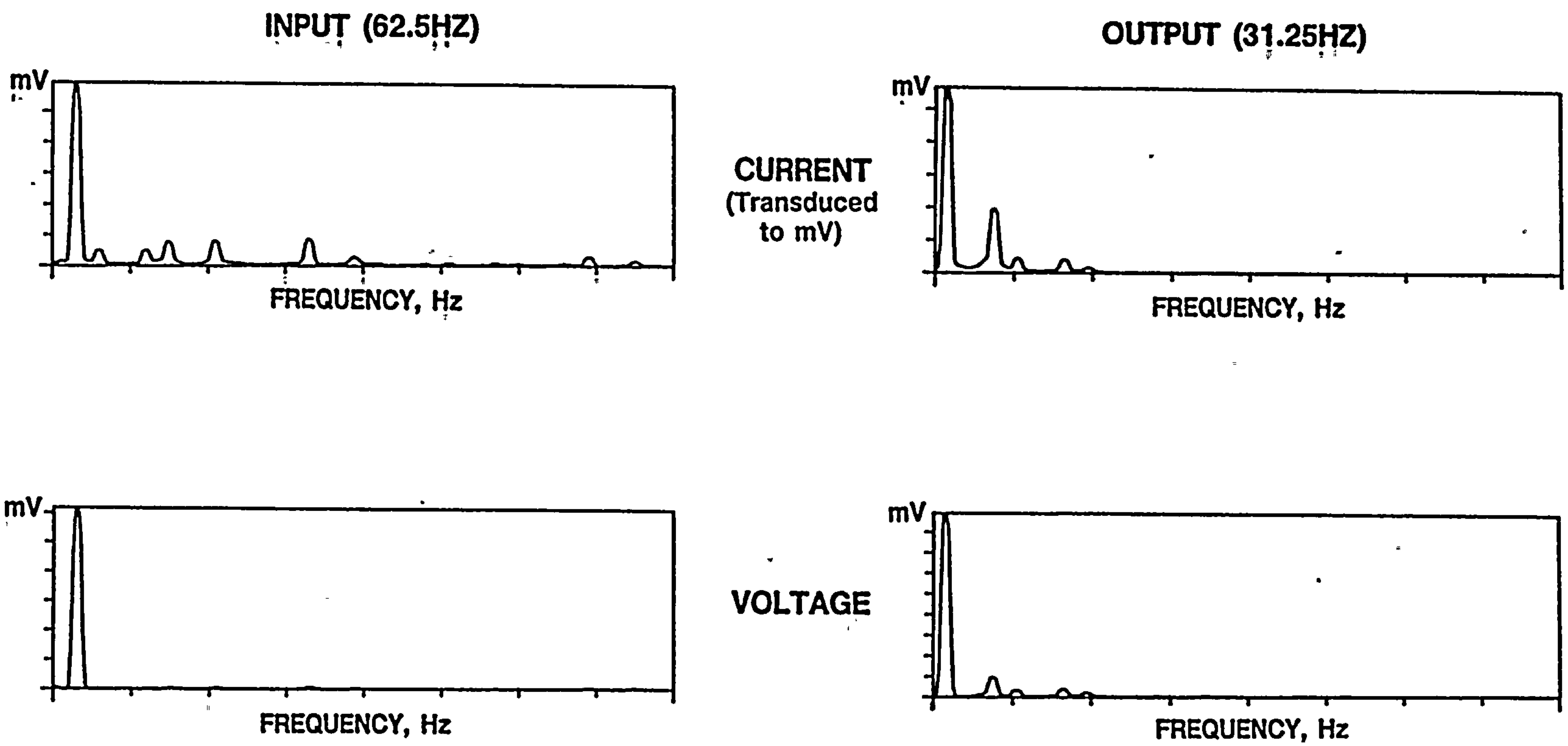


Figure 6-13
IOWA PUBLIC SERVICE COMPANY - NEAL PLANT
12-PULSE, 6-PULSE OUTPUT
MODIFIED LCI ASD

Table 6-1

IOWA PUBLIC SERVICE CO.

NEAL 2 CONSTANT PRESSURE - SLIDING PRESSURE TEST DATA

DATA POINT	UNITS	CONSTANT PRESSURE TEST 7/28/88				VARIABLE PRESSURE TEST 7/29/88			
		TIME				TIME			
		0900	1000	1100	ACCUM/ AVG	0900	1000	1100	ACCUM/ AVG
NET LOAD	MWH	118	120	122	120	120	120	120	120
DRUM PRESSURE	PSIG	2452	2453	2452	2452	1101	1101	1101	1101
MAIN STM PRESS	PSIG	2441	2442	2442	2442	1042	1043	1042	1042
THR STM PRESS	PSIG	2402	2400	2400	2401	1021	1021	1021	1021
NET HEAT RATE	BTU/KWH				10542				10298
MILL A COAL FLOW	TONS	27.85	28.30	28.30	84.65	27.90	27.45	27.40	82.75
MILL B COAL FLOW	TONS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MILL C COAL FLOW	TONS	28.05	28.50	28.70	85.25	28.00	27.60	27.55	83.15
MILL D COAL FLOW	TONS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
COAL HEATING VALUE	BTU/LB				11169				11173
GAS FLOW	MCF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LOWER SPRAY FLOW	MPPH	16.78	16.56	16.78	50.12	22.19	25.47	26.92	74.58
UPPER SPRAY FLOW	MPPH	6.87	2.22	1.32	10.41	11.48	14.90	18.35	44.73
GROSS LOAD	MWH	130	134	132	132	128	130	128	129
AUX A LOAD	MWH	6	8	6	7	4	6	4	5
AUX B LOAD	MWH	6	6	4	5	4	4	4	4
BFP A DISC PRES	PSIG	2914	2918	2914	2915	1525	1527	1526	1526
BFP B DISC	PSIG	2891	2893	2889	2891	1483	1485	1485	1484
MAIN STM TEMP	DEG F	958	971	979	969	1010	1010	1010	1010
THR STAM FLOW	MPPH	826	828	810	821	838	837	840	838
THR STEAM TEMP	DEG F	962	975	983	873	1015	1014	1014	1014
FIRST STG PRESS	PSIG	631	636	627	631	661	657	660	659
COLD RH @ TURB PRESS	PSIG	209	210	206	208	204	204	205	204
COLD RH @ TURB TEMP	DEG F	485	495	500	493	643	642	643	643
COLD RH @ BLR TEMP	DEG F	485	496	502	494	642	641	642	642
HOT RH @ BLR TEMP	DEG F	850	854	863	856	951	956	957	955
HOT RH @ BLR PRESS	PSIG	186	186	183	185	180	160	161	160
RSH TUBE 10 TEMP	DEG F	791	793	795	793	822	825	827	825
RSH TUBE 20 TEMP	DEG F	824	825	830	826	869	871	873	871
FSH TUBE 10 TEMP	DEG F	895	905	913	904	936	939	939	938
FSH TUBE 20 TEMP	DEG F	899	907	909	905	914	907	906	922
RHTR TUBE 10 TEMP.	DEG F	803	809	820	811	918	923	926	922
RHTR TUBE 20 TEMP	DEG F	349	350	353	351	385	386	385	385
AHTR GAS IN TEMP	DEG F	521	523	528	524	559	560	561	560
BLR BLOWDOWN SILICA	PPB	57.80	56.04	54.18	56.01	68.67	76.48	83.59	76.25

HEATRATE SAVINGS WITH VARIABLE:245 BTU/KWH
PRESSURE AT 120 MW NET LOAD: 2.32%

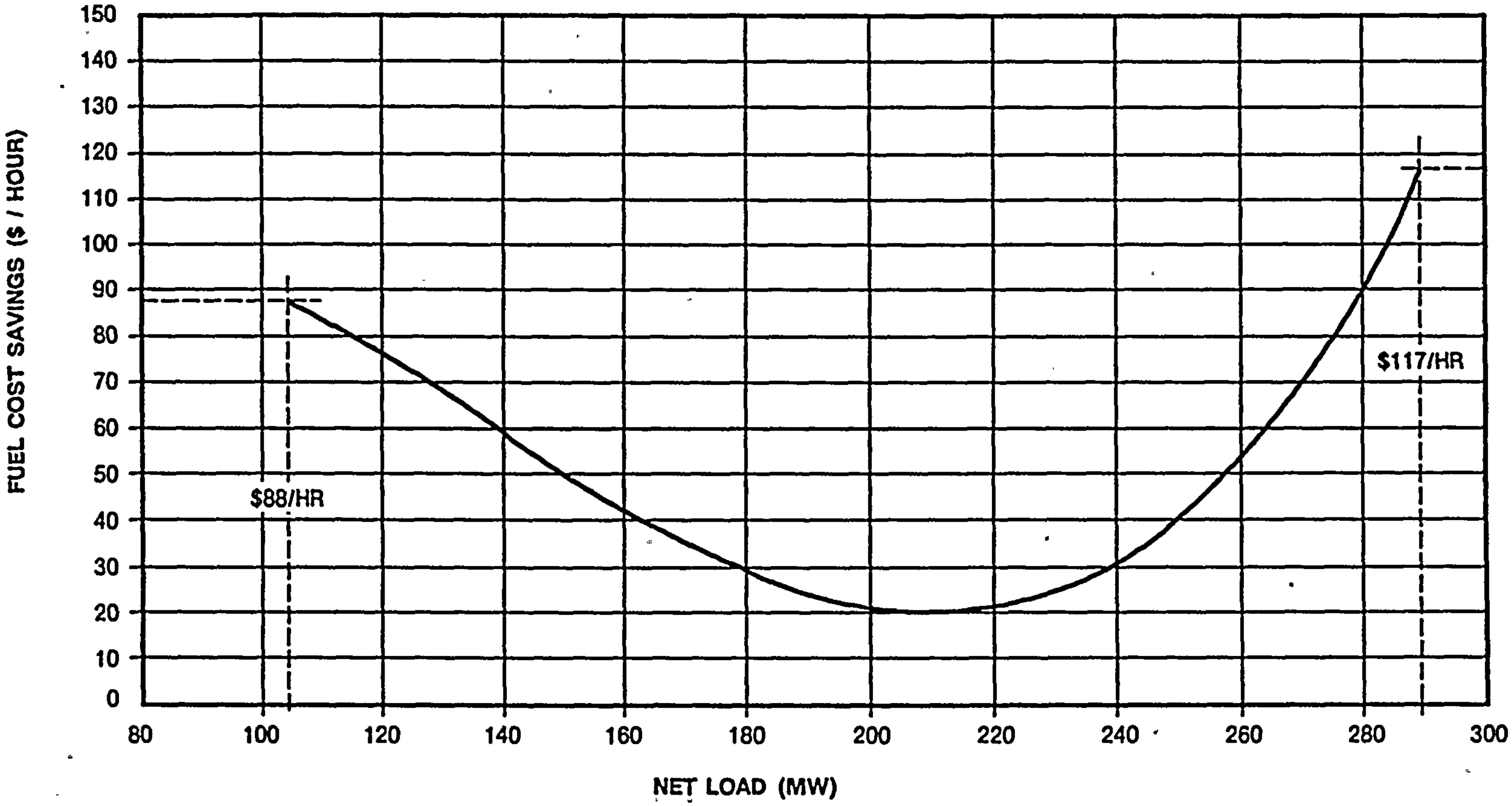


Figure 6-14

IOWA PUBLIC SERVICE CO. – NEAL 2

VARIABLE PRESSURE – FUEL COST SAVINGS

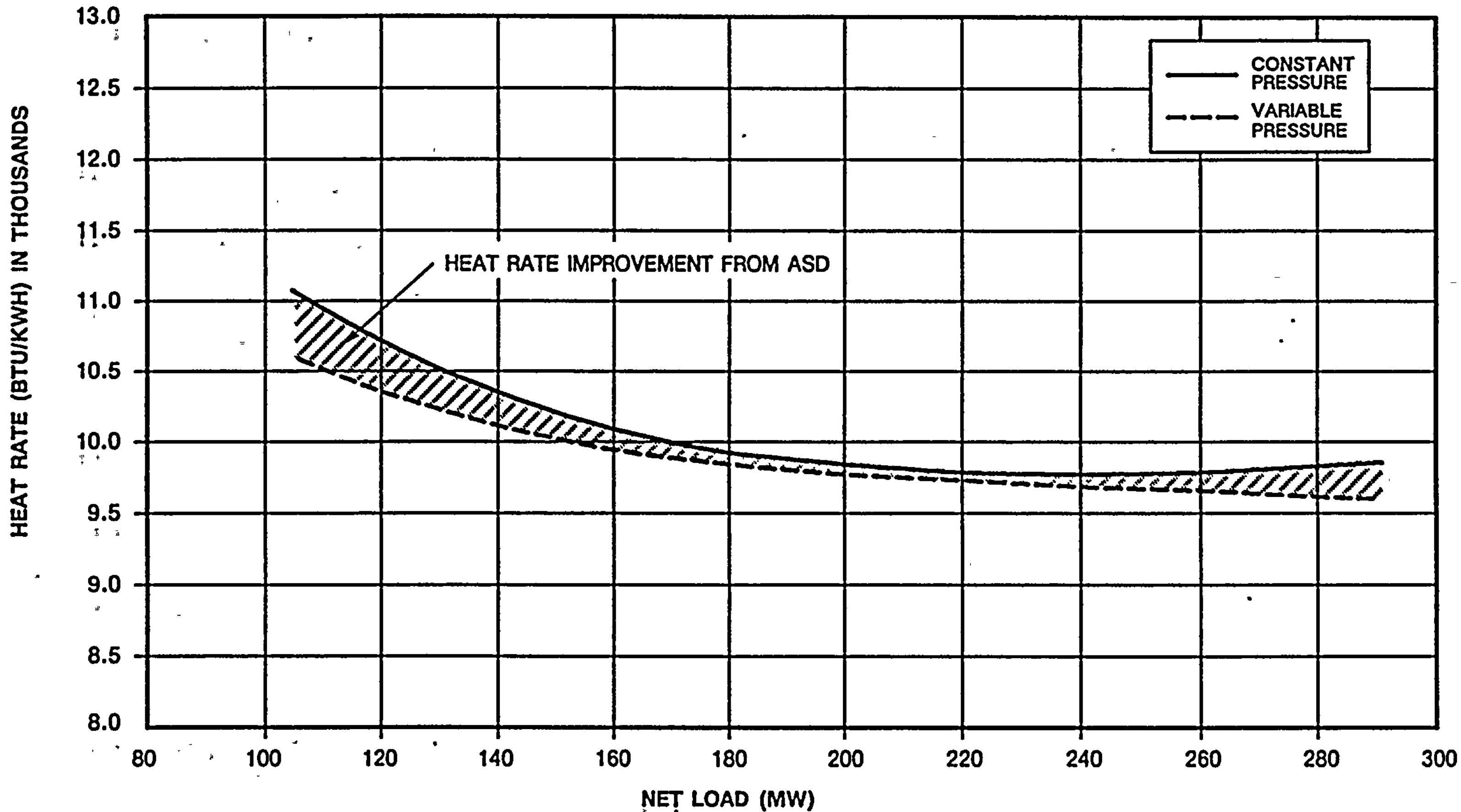


Figure 6-15

IOWA PUBLIC SERVICE CO. - NEAL 2

VARIABLE PRESSURE - HEAT RATE COMPARISON

Table 6-2

IOWA PUBLIC SERVICE CO. - NEAL 2

FUEL COST SAVINGS PER YEAR - 1988-89

LOAD MW	FUEL COST $/MMBTU	DIFF HEAT RT MMBTU/HR	COST SAVINGS $/HR	OCT, 1988 1988 HOURS	THROUGH 1988 $ SAVINGS	JUNE, 1989 1989 HOURS	1989 $ SAVINGS
1	1.599	52.772	$84.38	4	$ 337.53	15	$1,265.74
21	1.599	52.772	$84.38	4	$ 338	6	$ 506
41	1.599	52.772	$84.38	3	$ 253	6	$ 506
61	1.599	52.772	$84.38	138	$ 11,645	260	$ 21,939
81	1.599	52.772	$84.38	103	$ 8,691	238	$ 20,083
101	1.599	52.772	$84.38	83	$ 7,004	374	$ 31,559
121	1.599	46.103	$73.72	131	$ 9,657	369	$ 27,202
141	1.599	35.911	$57.42	457	$ 26,242	419	$ 24,060
161	1.599	25.89	$41.40	206	$ 8,528	196	$ 8,114
181	1.599	17.749	$28.38	180	$ 5,109	179	$ 5,080
201	1.599	13.088	$20.93	150	$ 3,139	144	$ 3,014
221	1.599	13.404	$21.43	109	$ 2,336	151	$ 3,236
241	1.599	20.087	$32.12	141	$ 4,529	147	$ 4,722
261	1.599	34.42	$55.04	122	$ 6,715	180	$ 9,907
281	1.599	57.583	$92.08	25	$ 2,302	30	$ 2,762
			TOTALS	1856	$ 96,824	2714	$ 163,956
						GRAND TOTAL	$ 260,780
						ANNUALIZED GRAND TOTAL	$ 347,707

power plant emissions. IPS engineers estimate the emissions savings for energy produced by the ASD installation to be on the order of 150 tons of SO_2 per year.

Table 6-2 shows the ASD generated savings for the period October 1988 through June 1989 of $260,780. Scaling this 9-month savings to 12 months results in an annual savings of $347,707. With the increased capacity covering the cost of the ASD installation, the $347,707 fuel cost saving is a direct efficiency improvement for the unit.

An excellent review of this installation is contained in Reference 10.

SLIDING PRESSURE OPERATION CONFIRMED

This installation of high power ASDs in a boiler feed pump application along with conversion of the unit to sliding pressure control confirms the benefits seen at Ft. Churchill on a smaller unit with gas firing. Neal 2 is a coal fired unit and even with lower fuel costs than originally expected, the fuel cost savings and increased plant capacity are worthwhile for IPS.

7. Sierra Pacific Power Company
Tracy Plant
Unit 3, Boiler Feed Pump
2000 HP ASD Field Test

Section 7

SIERRA PACIFIC POWER COMPANY, TRACY PLANT
UNIT 3, BOILER FEED PUMP, 2000 HP ASD FIELD TEST

UNIT DESCRIPTION AND PURPOSE OF PROJECT

Tracy Unit 3 generating unit is a duplicate unit of the 110 MW Units 1 and 2 at Ft. Churchill. Based on the excellent results obtained with the ASD installation on the 2A Boiler Feed Pump at Ft. Churchill, Sierra Pacific Power decided to convert the 3A Boiler Feed Pump at Tracy Unit 3 to adjustable speed. Operating benefits were expected to be very similar to those realized at Ft. Churchill.

DESCRIPTION OF APPLICATION

At Tracy, Sierra Pacific decided not to relocate the control valve on the basis that the valve could be left fully open with 3A pump operating, but would be available for control of the 3B pump. This unit operates in similar manner to Ft. Churchill, with the 3A pump operating at loads up to 75 MW and the 3B pump available for load up to full load. An isometric view of the Tracy ASD installation is in Figure 7-1.

ASD TECHNOLOGY

EPRI included this project in its field test program because it completed the technology evaluation story that began in 1983. The 6-pulse input and 6-pulse output current-source, gate-turn-off (GTO) current source inverter has the ability to eliminate the 5th, 7th, 11th and 13th harmonics to the motor at certain frequencies by PWM control of the output waveform thus minimizing electrical resonance between the motor and the output filter. At Tracy, the ASD consists of a 4000/4000V input transformer, a 6-pulse rectifier, a dc link inductor, a 6-pulse GTO-PWM inverter, an output capacitor filter and a by-pass switch arrangement. The electrical system arrangement is in Figure 7-2. The circuit for the Tracy Unit 3 ASD is shown in Figure 7-3.

OPERATING EXPERIENCE

The Tracy 3 boiler feed pump ASD went into service in mid-1987 and encountered a number of GTO failures similar to the troubles at the OG&E Seminole ASD and the

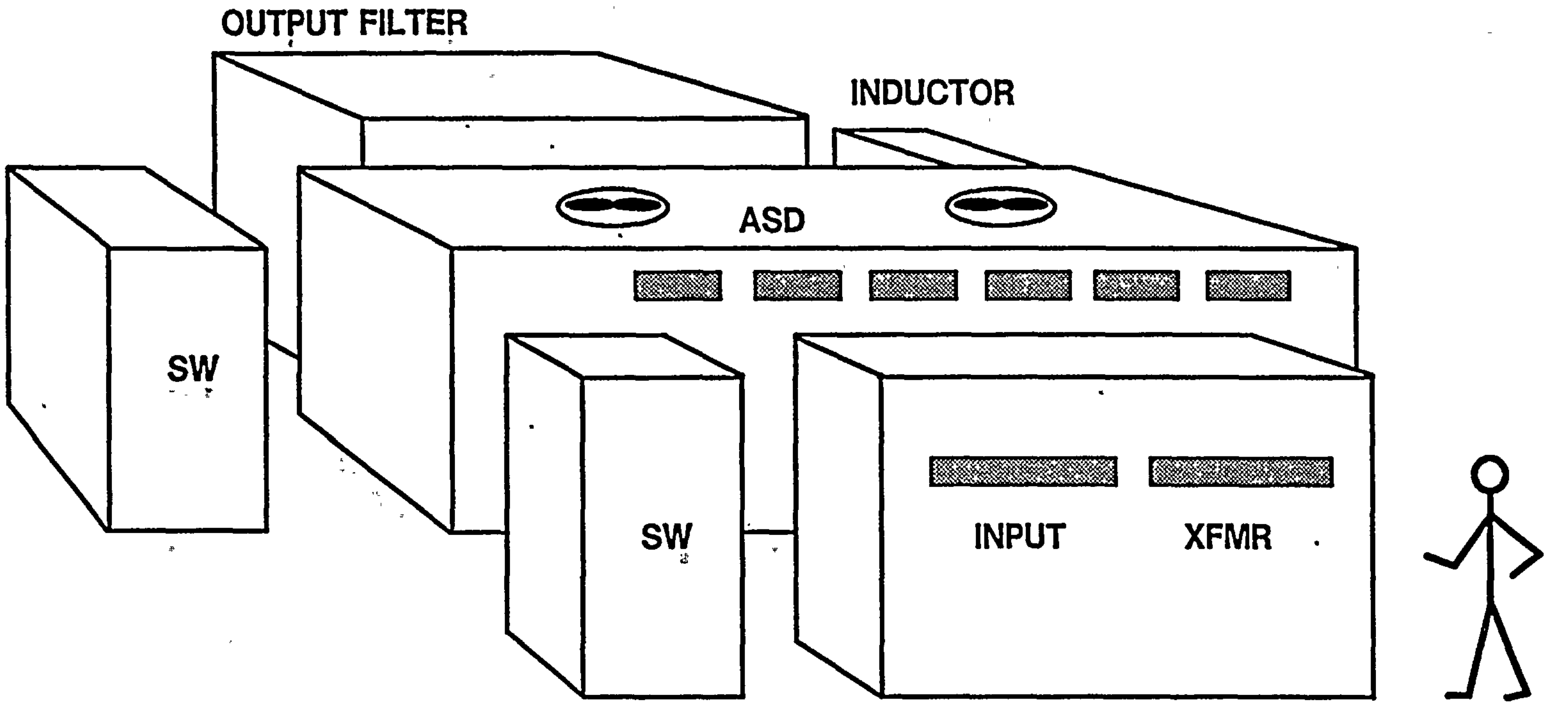


Figure 7-1
TRACY UNIT 3
ISOMETRIC VIEW ASD INSTALLATION

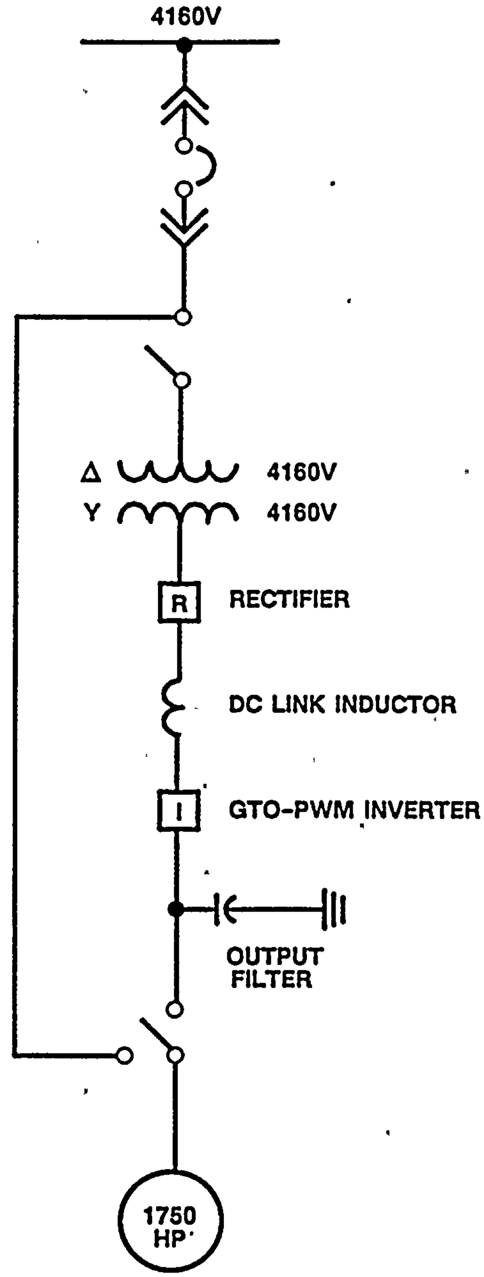


Figure 7-2

SIERRA PACIFIC POWER CO.
TRACY PLANT UNIT 3
2000HP BOILER FEED PUMP ASD

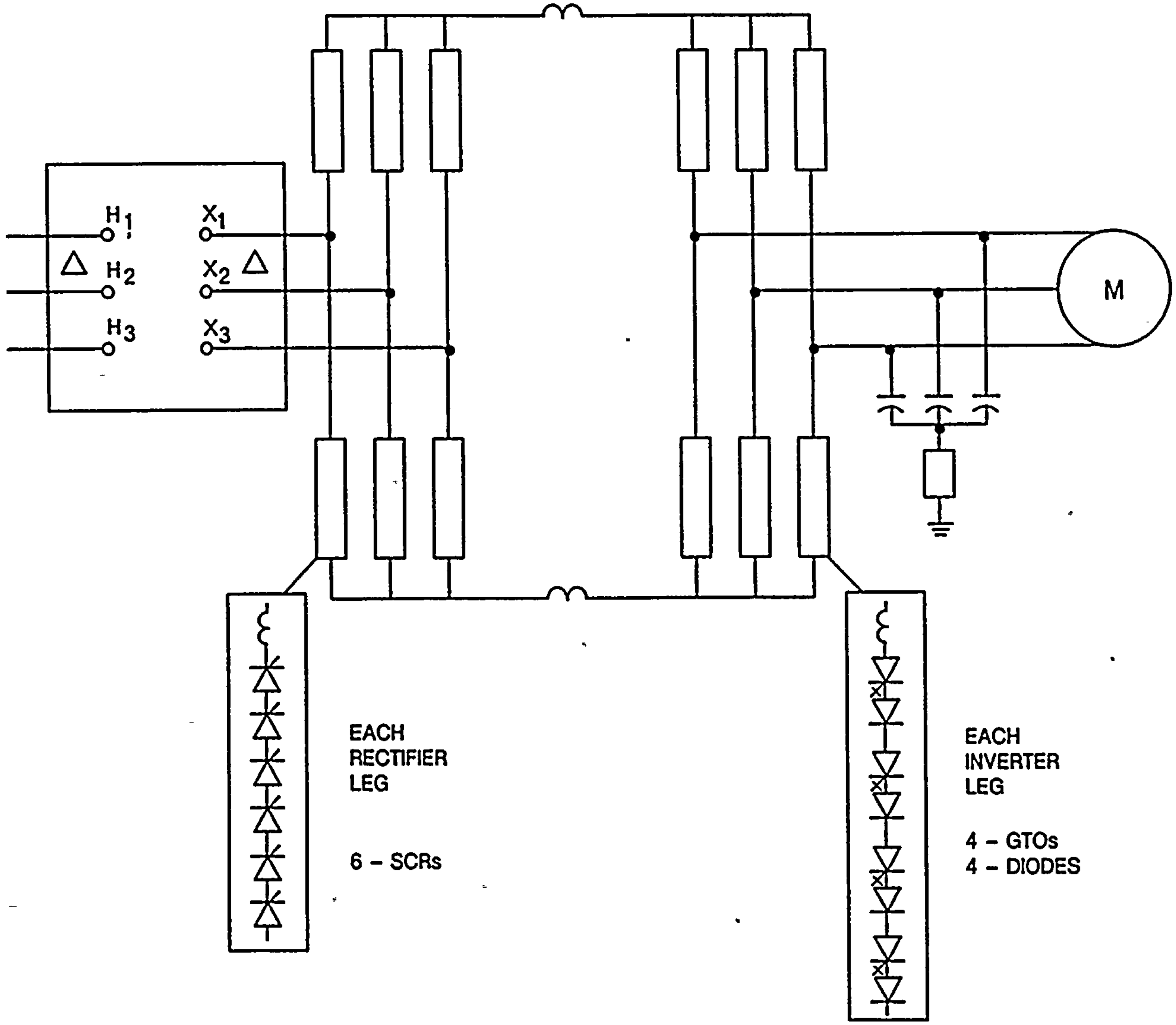


Figure 7-3
TRACY PLANT
2000HP CURRENT SOURCE GTO PWM 6-PULSE ASD

IPS Neal ASD installations. After the GTO application problems were resolved in late 1987, the Tracy 3 ASD has performed without trouble. The by-pass switch arrangement shown in Figure 7-2 used vacuum contactors and was very useful when the GTO application problems were being resolved.

While the Tracy 3 and Ft. Churchill 2 units have duplicate boilers, they have different turbine-generators. Ft. Churchill has a General Electric turbine-generator and Tracy 3 has a Westinghouse turbine-generator. The necessary revisions to the turbine control to achieve the low minimum loads at Tracy 3 had not been made when the ASD tests were made. Consequently, the economic performance at Tracy was not comparable to that seen with the ASD installation at Ft. Churchill Plant.

TEST RESULTS

Power measurements were taken in June of 1988 at the following loads:

20 MW
40 MW
55 MW
75 MW

The feed pump was operated on the ASD and on the electrical by-pass for each load point. This allowed direct measurement of the power on valve control and on ASD control. From the power measurements, input and output total harmonic distortion was determined and are shown in Table 7-1. Input and output current and voltages are shown in Figures 7-4 and 7-5. Of interest is the very low 2.2% voltage distortion at the input of this 6-pulse ASD with input transformers. This shows that a 2000 HP ASD can be selected with 6-pulse configuration with input voltage THD significantly below the 3% value that has been used in the five EPRI sponsored ASD installations.

RESULTS OF RETROFIT

The kw input on by-pass and on ASD are plotted in Figure 7-6 along with the kw savings vs load.

Power consumption on the by-pass connection reflects operation of the boiler feed pump with valve control of flow and with constant boiler pressure. Power consumption on the ASD control is also with constant boiler pressure. While the

Table 7-1

TRACY PLANT, UNIT 3
BOILER FEED PUMP ASD
FIELD RESULTS

UNIT MW	HP	MOTOR FREQ.	RPM	% EXTRA MOTOR LOSS	HARMONICS				ASD EFF
					INPUT		OUTPUT		
					THD-V	THD-I	THD-V	THD-I	
75	1722	60	3565	0.6	2.2	24.7	9.0	10.8	.983
55	1350	56.25	3342	0.9	1.6	24.8	9.3	10.8	.989
40	1053	56.25	3342	0.9	1.9	24.8	8.7	15.8	.981
20	697	50	2970	1.2	1.4	24.9	10.0	18.8	.983

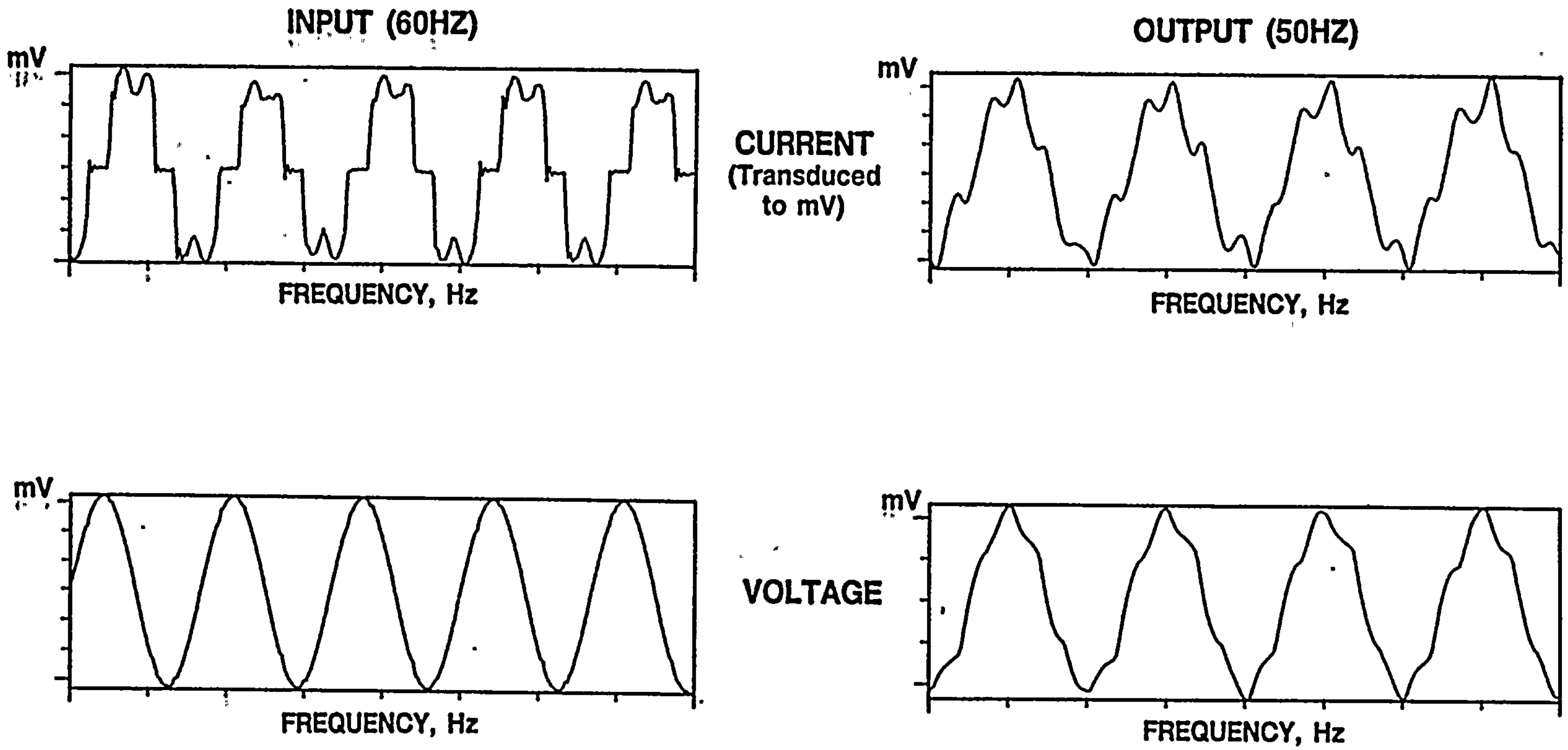


Figure 7-4
SIERRA PACIFIC POWER COMPANY - TRACY PLANT
6-PULSE INPUT, 6-PULSE OUTPUT GTO-PWM
CURRENT SOURCE ASD

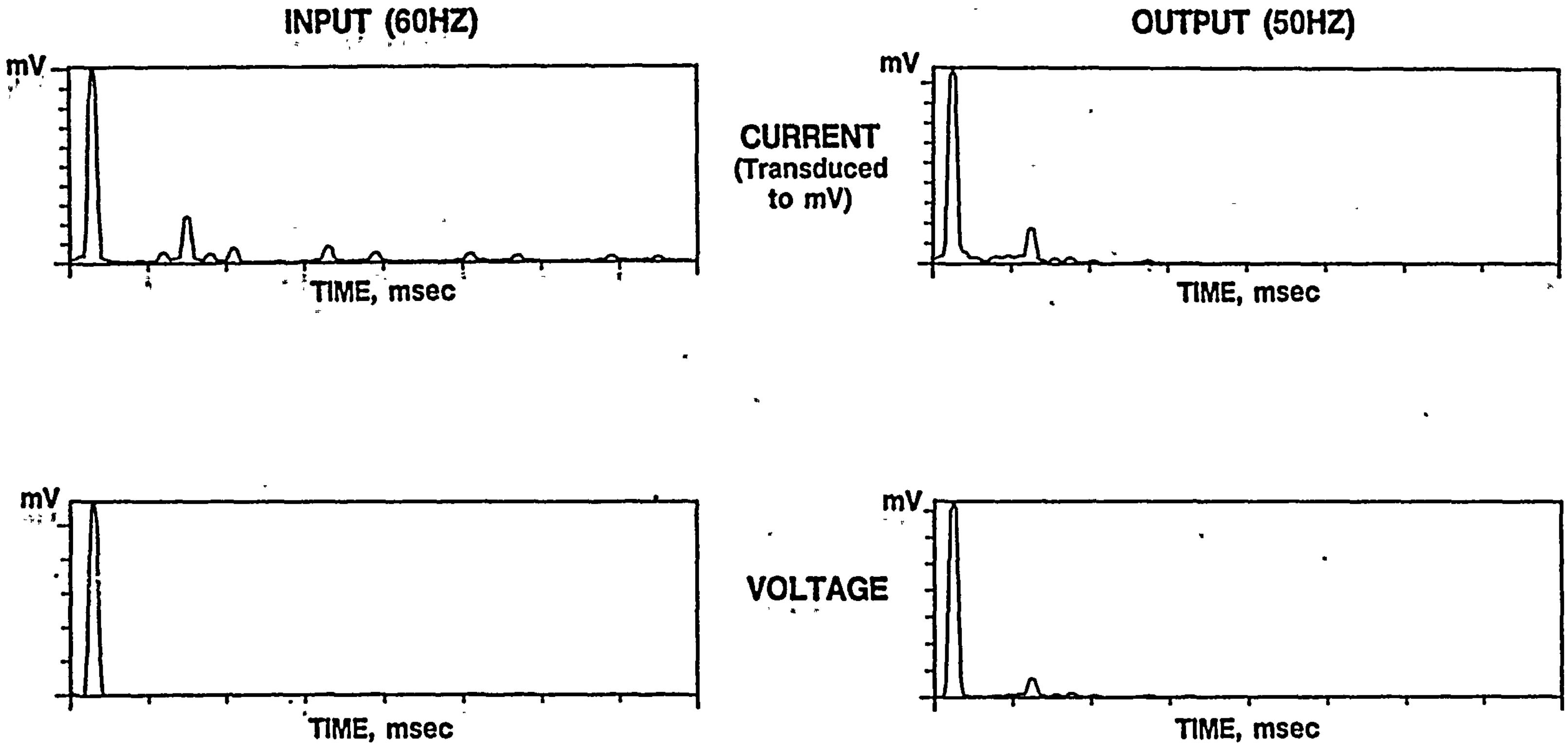
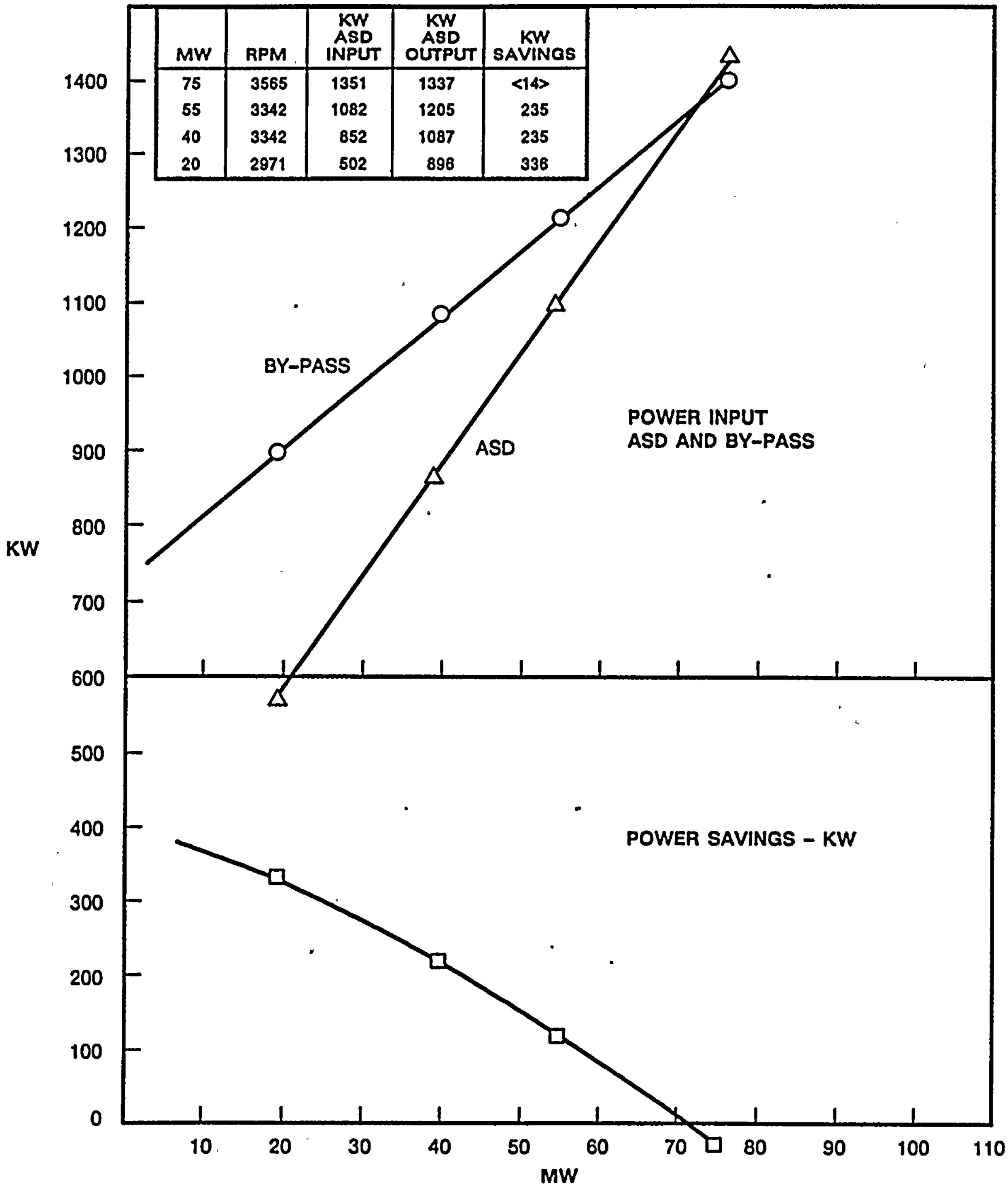


Figure 7-5
SIERRA PACIFIC POWER COMPANY - TRACY PLANT
6-PULSE, 6-PULSE OUTPUT GTO-PWM
CURRENT SOURCE ASD



MW	RPM	KW ASD INPUT	KW ASD OUTPUT	KW SAVINGS
75	3565	1351	1337	<14>
55	3342	1082	1205	235
40	3342	852	1087	235
20	2971	502	896	336

Figure 7-6
TRACY PLANT UNIT 3
BOILER FEED PUMP ASD

savings are nowhere near as great as seen at Ft. Churchill, with reduced boiler pressure, the savings are significant enough to earn a respectable payback.

Annual savings at Tracy are estimated at $80,000 with a simple payback of 3.4 years.

WHAT IS THE GTO'S EFFECT ON ASD DESIGN AND PERFORMANCE: COMPARISON OF FT. CHURCHILL AND TRACY INSTALLATIONS

Description of ASD Equipment

The ASD technologies used in the two installations are different. The ASD that was installed at Ft. Churchill in 1984 was typical for ASDs of that time. It is a 12-pulse input, 12-pulse output ASD with a current-source inverter. The 2000 HP motors at both plants are duplicates and are rated for 4000V. The Ft. Churchill ASD has a 900 volt dc link and it requires input and output transformers. The power circuit for this ASD is shown in Figure 3-3.

Each rectifier bridge for the Ft. Churchill ASD uses a single thyristor in each leg. Each inverter bridge leg uses a single thyristor plus a blocking diode and commutation capacitor. Thus, there are 24 thyristors, 12 diodes, and 6 capacitors in the ASD.

Figure 7-3 shows the power circuit for the ASD used at Unit 3 at Tracy Plant. It represents state-of-the-art technology for 1987. It has an input transformer, a 6-pulse rectifier, a 4000 volt dc link, and a 6-pulse current-source GTO-PWM inverter with an output filter capacitor. The rectifier bridge contains 36 thyristors. The inverter has 24 GTO thyristors and 24 blocking diodes for a total of 84 power semiconductors. This ASD is capable of operation with one thyristor out of service in each leg in both the rectifier and in the inverter. Both ASDs have microprocessor controls. The blocking diodes were used because the GTOs are of the unsymmetrical type.

These two installations show the changes that have been made in ASDs for large motors over the period of the past few years. The 12-pulse input, 12-pulse output system has basically been superseded by a 6-pulse input, 6-pulse output system with output capacitor filter. This simplification has resulted in a cost saving for the project of about 30 percent.

Power Savings - Advantage of Sliding Pressure

Comparison of the boiler feed pump horsepower at the two stations appears in Figure 7-7.

The Ft. Churchill boiler feed pump, operating with the unit at minimum load and reduced boiler pressure, runs at 200 horsepower. With constant speed operation, constant pressure operation and valve control, the horsepower was previously measured at 940 HP. This reduction in power for a year's time at 8000 hours per year results in saved energy of 4.4 x 10^6 kwhr.

At Tracy, with a load duration curve as depicted in Figure 7-8 and without conversion to sliding pressure operation, motor horsepower at 20 MW minimum load drops to 750 HP from 1700 HP with the ASD. The energy savings were 2.0 x 10^6 kwhr per year.

At Ft. Churchill, the total value of reduced power output from the unit and increased efficiency of operation has been estimated at $1.6 million per year. Without the benefit of sliding pressure operation and with no reduction in minimum load, the annual savings at Tracy Unit 3 with the load curve of Figure 7-8 have been evaluated at $88,000 per year.

Harmonic Distortion - Voltage and Current

Table 7-2 shows that voltage distortion can be controlled equally well with a 6-pulse input or a 12-pulse input for a 2000 HP ASD in this size power plant. There is significantly more current distortion at the input for the 6-pulse drive. No problems have been identified with other auxiliary equipment or control systems that can be related to the higher level of current distortion.

A comparison of current and voltage distortion at the motor terminals is also shown in Table 7-2. The GTO-PWM inverter offers better control of voltage harmonics at the motor by not producing the high frequency spikes seen in output of the 12-pulse current-source inverter. However, the basic sine wave of the 12-pulse system is better as evidenced by the lower current harmonics. The current harmonics produced by the GTO-PWM inverter are entirely acceptable for this application as evidenced by no noticeable extra motor heating or vibration.

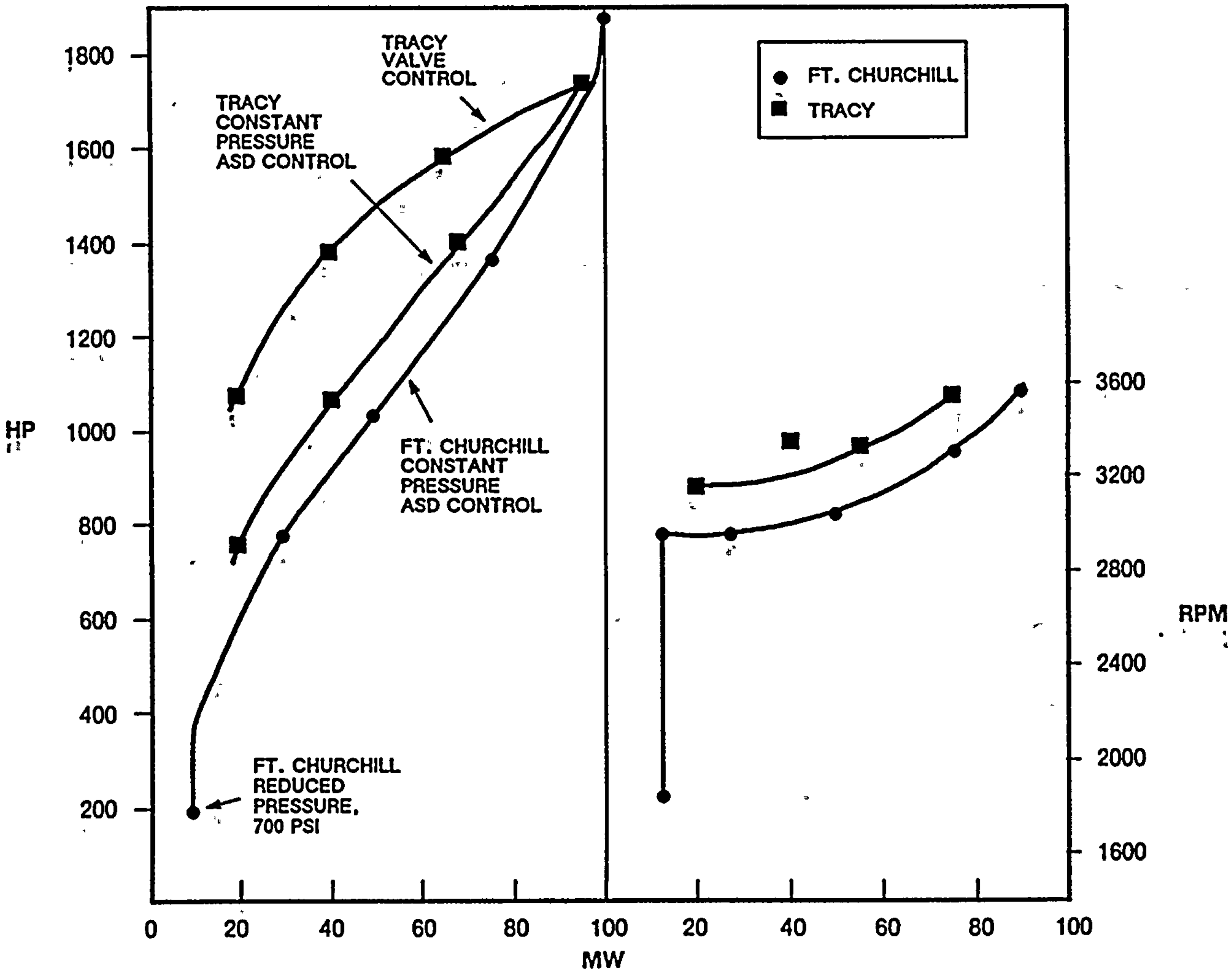


Figure 7-7

COMPARISON OF FT. CHURCHILL AND TRACY 2000HP ASDs

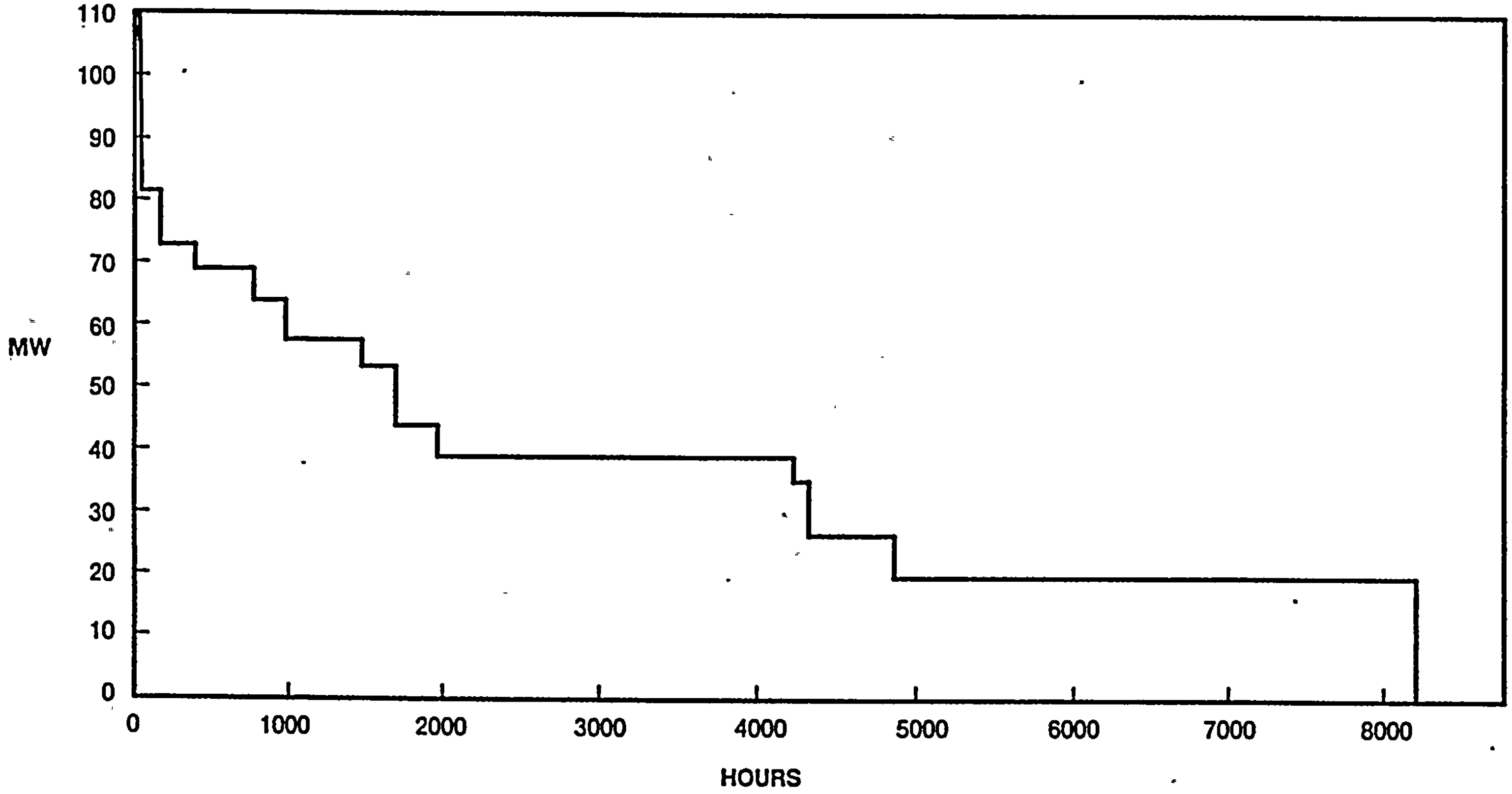


Figure 7-8

TRACY PLANT UNIT 3 - 1988

ANNUAL DURATION LOAD CURVE

Table 7-2

COMPARISON OF HARMONIC DISTORTION OF ASDs AT FT. CHURCHILL AND TRACY

FT. CHURCHILL 2 12-PULSE INPUT, 12-PULSE OUTPUT			TRACY 3 6-PULSE INPUT, 6-PULSE OUTPUT		
MW	% THD VOLTAGE	% THD CURRENT	MW	% THD VOLTAGE	% THD CURRENT
90	2.4	10.7	75	2.2	24.7
75	2.3	11.0	55	1.6	24.8
50	2.1	11.4	40	1.9	24.8
25	1.9	11.9	20	1.4	24.9
12	1.0	10.9			

8. Summary

Section 8

SUMMARY

ASD EQUIPMENT

EPRI has provided a strong leadership role in the development of a sophisticated power-electronics-based technology for converting fixed-speed squirrel cage induction motors in power plants to adjustable-speed operation. Although a number of inverter technologies have been found to exist commercially for large motors, three U.S. designed technologies have survived the rigors of competition. They are as follows:

- Current-source
- Modified load commutated (modified LCI)
- Current-source GTO-PWM

Of these three, the latter two are still being successfully sold for large motors (2000 HP and larger). The current-source system has been shown to have a number of excellent features at the Sierra Pacific Power, Ft. Churchill Plant on the Unit 2 boiler feed pump. It has good harmonic control when used in a 12-pulse input, 12-pulse output configuration, it has no output filter capacitor requirement, and can be used in a full regenerative braking mode.

The modified LCI inverter, another form of current-source technology, has provided an economic ASD system that has shown the utility industry that it can reduce fuel costs in many motor applications with electronic speed control. The modified LCI system has the simplicity afforded by a rectifier and inverter using the same components. The dc link diverter circuit provides for inverter commutation when the output filter capacitor can no longer provide excitation to the induction motor to allow LCI operation. This system has been packaged with water cooling of the power electronics to simplify the overall cooling system. Water cooling is important for many power plant applications where the air is contaminated with coal or ash dust.

The modified LCI system has been offered in a 6-pulse input, 6-pulse output arrangement without an input transformer and with an output filter capacitor of

about the motor KVA rating. Experience has shown that there are two problems with this concept. First, without the input transformer excessive line-to-ground voltages can develop. As the result of applying this ASD without an input transformer, motor winding failures have occurred in form wound stator coils. Form wound coils are generally used in motors rated 2300 volts and higher. Form wound coils are made with rectangular cross-section wire. The coils are preinsulated and shaped to fit the stator slots with minimum clearance. Motors rated 575 volts and lower use a random wound insulation system which has more voltage margin; ASDs without input transformers have been widely successful on the lower voltage motors.

The input transformer, along with a system ground near the motor terminals, eliminates this overvoltage problem. Once a decision has been made to use an input transformer, the rectifier can be configured in a 12-pulse arrangement at very little extra cost to eliminate the powerful 5th and 7th harmonics to the auxiliary busses. This feature by itself is usually enough justification for the use of an input transformer.

A second problem has surfaced with the modified LCI system. The large output capacitor filter can lead to a resonant circuit with the motor's leakage reactance at about 50% speed. Resonance has been observed with the 5th harmonic current in measurements at Willow Glen Plant.

While this condition caused no problems at Willow Glen on the high speed, low inertia boiler feed pump, there have been other instances reported on high inertia fan applications of motor shaft vibration and fatigue that is related to high 5th or 7th harmonic currents in the motor windings. Shaft torsional vibration on high inertia fans is now being avoided by shifting the electrical resonance frequency with output reactors. Because of the potential for frame vibration, shaft torsional vibration, and foundation vibration when operating this inverter on high inertia fans in the region of electrical resonance between the filter and the motor, the user may wish to specify a limit on any single output current harmonic not exceeding 15% of the fundamental at any frequency. An output 5th harmonic of less than 15% would be expected for a 6-pulse inverter, with filter, operating without an electrical resonance condition.

Another version of the modified LCI system was tested at Iowa Public Service, Neal Unit 2 on 2-7000 HP boiler feed pumps. This system with input transformers and

12-pulse rectifiers has a GTO diverter circuit. The GTO link commutator circuit controls the output harmonics to avoid filter resonance.

Both the modified LCI and current-source GTO-PWM technologies use large inductors in the dc link. This makes both of these systems current-source type systems rather than voltage-source systems. The advantage of the current-source system is that the large dc link inductor limits the fault current to the inverter and misfiring of inverter power devices does not result in shutdown. The voltage source system which is widely used in ASDs rated 5 HP to 200 HP with power transistors is available in large ASDs manufactured by overseas companies. They have not been competitive in price in the U.S.

The current-source GTO-PWM inverters being demonstrated in this EPRI field test program represent the highest degree of technology available at the time of these tests. The pulse width modulation technology along with a smaller output filter allows wave shaping at all inverter outputs giving the effect of a 12-pulse or 18-pulse inverter with a single 6-pulse bridge. Resonance between the motor and output filter is eliminated by omission of the offending frequency with PWM control.

The complex PWM operating system requires the use of microprocessor control to change the pulse width patterns with frequency. At full speed, the output is a filtered square wave without PWM wave shaping.

This concept was tested at two locations under this EPRI study. The Oklahoma Gas & Electric Co. Seminole Plant, Unit 1 installation of 2-5500 HP FD Fan ASDs and the Sierra Pacific Power Co. Tracy Plant, Unit 3, 2000 HP Boiler Feed Pump ASD installation.

ECONOMICS

The field test program shows that there are good economics to be obtained in ASD retrofits. The economic study needs to be done with accurate information. Table 8-1 lists the results of these five retrofits.

It has been clearly shown that boiler feed pump motor retrofits provide excellent payback if the unit is operating with sliding pressure. All retrofits are sensitive to annual load duration curve and fuel cost. In many cases load duration and fuel costs are difficult to predict.

Table 8-1

ECONOMIC SUMMARY ASD RETROFITS

STATION	ASD APPLICATION	ANNUAL SAVINGS	YEARS PAYBACK
FT. CHURCHILL	2-1000 HP BOILER FEED pp	$1,600,000	.3
WILLOW GLEN	1-2250 HP BOILER FEED pp	130,000	2.5
NEAL	2-7000 HP BOILER FEED pp	348,000	7.7
SEMINOLE	2-4000 HP FD FANS	231,000	5.4
TRACY	1-2000 HP BOILER FEED pp	80,000	3.4

HARMONICS

Tables 8-2 and 8-3 summarize the harmonic levels measured in these tests. The results show that voltage harmonics to the system can be kept to low levels. This suggests that, before selecting, the 12-pulse or 6-pulse transformer connection, both alternatives need to be evaluated for lowest cost.

At the time of these tests, we do not have standards that provide limits for harmonic levels at the input to the motor. A wide range of current and voltage harmonics, as listed in Table 8-3, have not caused motor problems in these tests, but as suggested earlier, for high inertia fans a limit should be considered.

RELIABILITY

All of the ASDs of these field tests have been reliable after periods of initial failures. After the problems were solved, there have been no complaints about reliability. In retrospect, with so much being learned by both manufacturers during this period of time, these learning curve problems were to be expected. It would appear that ASDs being applied now should not have a design concept related failure profile.

APPENDIX

Major outputs of these tests include the ASCON II economic analysis computer program, the evolution of the ASD specification, and the evaluation of over 50 utility generating units for ASD retrofit economics.

To aid engineers in using this new technology, an Appendix has been provided in this report where valuable background information is isolated and presented in a distilled format.

Table 8-2
SUMMARY ASD INPUT HARMONICS - 4kV BUS
PERCENT TOTAL HARMONIC DISTORTION

FT. CHURCHILL

MW	FREQ.	THD - V	THD - I
90	60.2	2.3	10.7
75	55.8	2.3	11.0
50	52.5	2.1	11.4
25	50.3	1.9	11.9
12	31.7	1.0	10.9

NEAL

MW	FREQ.	THD - V	THD - I
270	50	3.60	17.3
180	43.8	2.88	18.0
90	37.5	2.67	23.9

WILLOW GLEN

MW	FREQ.	THD - V	THD - I
115	58	2.05	24.8
80	50	1.49	25.7
40	44	.99	26.6
15	35	.70	35.3

TRACY

MW	FREQ.	THD - V	THD - I
75	60	2.2	24.7
55	56.25	1.6	24.8
40	56.25	1.9	24.8
20	50	1.4	28.9

SEMINOLE 1A

MW	FREQ.	THD - V	THD - I
400	50	5.16	14.1
300	43.75	5.10	14.8
250	40	4.7	16.7
150	43.75	5.3	12.8

SEMINOLE 1B

MW	FREQ.	THD - V	THD - I
400	49.05	5.3	14.1
300	43.75	5.2	14.8
250	39	4.5	16.7
150	43	4.5	12.8

Table 8-3
SUMMARY ASD OUTPUT HARMONICS - AT MOTOR
PERCENT TOTAL HARMONIC DISTORTION

FT. CHURCHILL

MW	FREQ.	THD - V	THD - I
90	60.2	10.6	9.3
75	55.8	16.4	9.6
50	52.5	16.0	9.4
25	50.3	16.7	9.5
12	31.7	24.6	8.6

NEAL

MW	FREQ.	THD - V	THD - I
270	50	11.2	11.2
180	43.8	7.6	8.8
90	37.5	9.8	28.5

WILLOW GLEN

MW	FREQ.	THD - V	THD - I
115	58	7.8	14.46
80	50	10.32	25.6
40	44	12.06	38.1
15	35	16.86	67.1

TRACY

MW	FREQ.	THD - V	THD - I
75	60	9.0	10.8
55	56.25	9.3	10.8
40	56.25	8.7	15.8
20	50	10.0	18.8

SEMINOLE 1A

MW	FREQ.	THD - V	THD - I
400	50	13.9	17.6
300	43.75	8.0	8.6
250	40	16.6	15.6
150	43.75	8.8	9.6

SEMINOLE 1B

MW	FREQ.	THD - V	THD - I
400	49.05	8.6	18.9
300	43.75	8.2	8.3
250	39	14.1	17.4
150	43	8.8	10.1

9. Conclusions

Section 9

CONCLUSIONS

This test program is bringing to the attention of EPRI members the remarkable advances in power electronics control of large induction motors in power plant applications. Different housings, different cooling systems, different rectifier arrangements, and different inverter technologies have been analyzed, and preferred ASD application procedures have been identified.

Because the application of adjustable-speed drive to large induction motors is a new technology, there have been a number of things learned in this series of studies during the period of 1984-1989 while the field tests were being undertaken. In this section some of the lessons learned are identified and conclusions are presented.

HARMONICS

The tests have demonstrated that the input transformer combined with a 12-pulse rectifier bridge can be used effectively to control the 5th and 7th harmonics (and multiples) from the input side of the ASD. This was demonstrated at Sierra Pacific, Ft. Churchill Plant, Oklahoma Gas & Electric, Seminole Plant and Iowa Public Service, Neal Plant. Also, concerning input harmonics, it is important that an input transformer be used for a secondary purpose of keeping dc out of the system, thus eliminating even harmonics. Even harmonics were seen at Willow Glen which did not have an input transformer. The use of an input transformer and a properly tuned rectifier and inverter should produce a harmonic profile at the input similar to that seen at Ft. Churchill in Figure 3-6 (Section 3, Figure 3-6).

For a single large motor with ASD on a single bus, the input harmonics result in a voltage total harmonic distortion of less than 3%. From the results of these field tests, 3% THD does not result in harmonic problems on the supply system.

The input harmonics from each of the test projects are summarized in Table 8-2. The voltage harmonics at OG&E are highest, in the range of 4.5 to 5.3% THD. This level seems to have resulted from the manufacturer having inadequate information

on the system arrangement. Both FD fan motors are fed from the same transformer at OG&E and it is not clear that the manufacturer understood this. At the 5.3% THD level at OG&E there have been some problems with harmonics affecting drum level controls and burner controls.

The concern with input harmonics is that they will affect adversely other equipment in the plant. From this work, it appears that at the 3% THD level there are no problems, but that there may be problems at the 5% level as seen at OG&E.

Output harmonics affect the operation of the motor. Voltage harmonics or spikes can harm insulation. Current harmonics can cause eddy current heating in the stator and rotor windings and current harmonics can cause torsional torque pulsations. Two manufacturers of ASDs supplied equipment that was analyzed in these field tests. Both use output capacitor filters to smooth the shape of the current wave for the motor. From Table 8-3 of output harmonic test results, it is seen that the 12-pulse output offers the lowest output current harmonics, followed by the GTO-PWM inverter.

There has been no evidence of motor heating in any of the motors observed in the field tests, either from hot motors or winding failures.

SHAFT VIBRATION

Vibration in induction motors is different from that seen in fans or pumps because of the magnetic pull that is present in the electric machine and the slip speed that is a characteristic of the induction motor. For instance, with a bent shaft the vibration will have the pattern seen in Figure 9-1. There are two levels of vibration, one where the magnetic pull of the stator pulls against the high spot and one where the high spot does not see the magnetic pull. These two levels exist because of the differences in speed of the stator rotating field and the rotor shaft which is called "slip".

A similar pattern can develop with a straight shaft that is not centered in the stator. The magnetic pull at the small air gap will cause a bending of the rotor and rotor lateral vibration.

According to the authors of Reference 8, torsional vibration can affect lateral vibration with a pulsation frequency of $Wm \pm Wp$, where Wm is the mechanical speed and Wp is the frequency of the torque pulsation.

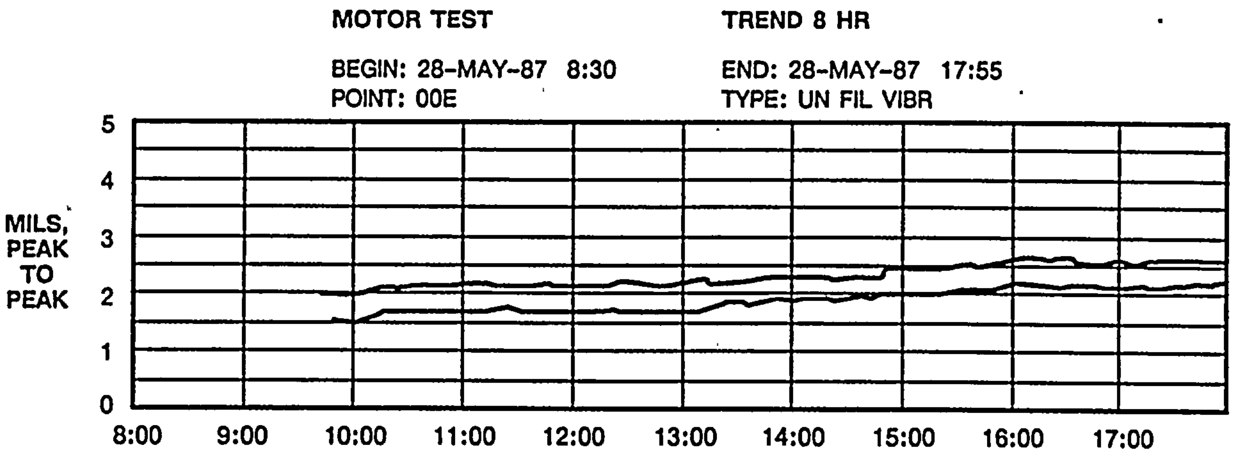


Figure 9-1

EFFECT OF MAGNETIC PULL ON SHAFT VIBRATION AMPLITUDE
3500HP, 3600 RPM INDUCTION MOTOR

There has been some evidence of torsionals being translated to heavy laterals with the modified load commutated inverter on large fan motors. The torsionals were developed by heavy 5th or 7th harmonic currents flowing when the output filter became resonant with the motor inductance. To correct this, reactors were added in series with the motors to shift the electrical resonance away from the shaft resonance. With the GTO-PWM inverter, this problem doesn't develop because the harmonics causing electrical resonance can be eliminated by notching the inverter output current waveform in specific patterns.

STATOR FRAME VIBRATION AND NOISE

The squirrel cage induction motor produces a series of forward and backward rotating magnetomotive force (mmf) harmonics that depend on the number of stator and rotor slots. The number of stator and rotor slots, called the slot combination, is selected based on design considerations and experience so that the rotor and stator harmonics do not combine to cause core and frame vibration and noise. When the motor is supplied from the ASD, the ASD generates a set of harmonics that also produce forward and backward rotating mmf harmonics. The ASD generated harmonics may excite a core and frame vibration that was eliminated in the original motor design. This condition has been observed on a motor driven by a GTO-PWM inverter which was not a part of this field test program. By adjusting the chopping frequency, it was possible to reduce the vibration and noise to a very low level that was acceptable.

Low level high frequency vibration has been seen on the FD fan motors at Seminole during the tests. This was the effect of ASD produced harmonics on the motor core.

POWER SAVINGS IN BOILER FEED PUMP MOTORS FROM SLIDING PRESSURE OPERATION

The results from operating the Ft. Churchill Unit 2 boiler feed pump at reduced boiler pressure with the ASD are documented in this report. Since the duplicate Tracy Unit 3 at Sierra Pacific Power has not been equipped to operate with sliding pressure, the test results from Ft. Churchill and Tracy offer a comparison of motor shaft horsepower when operating with and without the ASD and also a comparison to the horsepower with sliding pressure operation.

Figure 7-7 shows boiler feed pump horsepower versus MW output for Tracy 3 on valve control and on ASD control and Ft. Churchill on ASD control. They both operate with constant throttle pressure down to minimum load, but at minimum load, boiler

pressure is reduced from 1780 psi to 700 psi and the boiler feed pump horsepower drops to about 200 HP. This compares to 1080 HP for Tracy at minimum load on valve control.

The use of adjustable speed drives on power plant boiler feed pumps in these projects has been shown to facilitate operation of the turbine and boiler with reduced pressure at low load conditions. This reduced pressure operation was demonstrated at Ft. Churchill Plant to produce substantial economic savings from better boiler and turbine efficiency at low load. Additional savings are derived from reducing minimum load so that the offset power production can be obtained elsewhere at lower cost. The use of the speed controlled pump for reducing boiler pressure is a key to reduced pressure operation since it eliminates the pressure drop across the control valve and associated valve maintenance costs. The power electronics provide a non-intrusive way to convert to adjustable speed since this system does not require physical changes in motor or pump. Also, the electronics provide a very flexible control system with excellent response in controlling boiler drum level. Reliability has been established by these installations to the extent that Sierra Pacific Power Company has continued to install ASDs on other large power plant equipment.

KEY FACTORS IN SPECIFYING ASDS

There are a number of factors that affect the cost of an ASD. Basically, these are the current capability, voltage capability, the cooling system, the housing, harmonic limitation requirements.

CURRENT CAPACITY

Factors that affect current capacity are as follows:

- Horsepower rating of ASD
- Acceleration rate
- Current limit

The purchaser of an ASD should establish the horsepower rating of the ASD. It can be equal to the motor full load rating, the motor service factor rating or it can be greater or lesser than these ratings. If it is known that the maximum horsepower required of the motor is always less than the motor rating, the ASD should be rated accordingly. On the other hand, if it is questionable that the motor is large enough and there is a possibility that the motor will be replaced

with a larger motor in the future, it may be wise to select an ASD rated larger than the existing motor.

The acceleration rate establishes the full current rating of the power semiconductors used in the ASD. To control cost, the acceleration rate should be specified no higher than necessary. The acceleration rate and the current limit are related. Too low a current limit will limit acceleration. Therefore, the acceleration rate should be specified, but the current limit should be left to the manufacturer.

VOLTAGE CAPACITY

The voltage capacity is established by the N+1 requirement. U.S. manufacturers generally recommend that one extra thyristor per leg be furnished in the rectifier and in the inverter. This requires 6 extra thyristors in each bridge, but it allows the ASD to continue to function without interruption with a thyristor shorted, in fact with a thyristor shorted in each leg. This has the effect of providing 25 to 33% extra voltage margin when all thyristors are working properly.

HARMONIC LIMITS

Input harmonics are generally controlled by the available system fault current, the impedance of the input transformer, and the choice of the 6-pulse or 12-pulse rectifier. If the input transformer configured for 12-pulse operation is not sufficient to limit harmonics, then an 18-pulse input or, alternately, an input filter, can be used to achieve the THD required. Before specifying THD it is recommended that the plant one-line diagram with impedances and available fault current be reviewed with the ASD manufacturer to get an approximation of the THD that can be achieved with 6-pulse or 12-pulse rectifier.

Because of the reliability demands on electric utility high horsepower ID Fans and FD Fans, it is not acceptable to introduce shaft torsional vibration, frame vibration, or foundation vibration into the system with the ASD. Means are available to control harmonics to the motor: 12-pulse inverter or GTO-PWM inverter. When specifying ASDs for high horsepower, high inertia power plant fans, limits should be established for the amplitude of current harmonics that enter the motor. This is best done by putting words into the specification limiting harmonics to the motor, as shown in the Sample Specification, Appendix D. Also, the manufacturer should perform a torsional resonance study and demonstrate that there are no limitations in the operation of the motor from ASD induced

vibration. Harmonics to the motor can also result in heating and stator coil insulation punctures. These should be addressed in the ASD specification, with the responsibility left to the ASD manufacturer.

UTILITY SPECIFIC ASD

The lessons learned in these five installations and from several other recent utility installations of induction motor ASDs have contributed to a concept for a second generation ASD specifically for power plants. Features of the power plant specific ASD are as follows:

- Use of input transformer for 12-pulse or 18-pulse converter
- Grounding of ASD system to stabilize dc link voltage and eliminate motor over-voltage
- Built-in design tolerance for bus voltage swings, spikes and interruptions
- Water-cooled thyristors for simplified and more effective cooling
- Control of or elimination of resonance between output filter and motor

The utility specific ASD is shown schematically, in Figure S-1 of Executive Summary.

FAN NOISE REDUCTION

The only fans evaluated in this series of field tests were the 4000 HP FD fans at Seminole Plant, Unit 1 of Oklahoma Gas & Electric Co. The reduction of fan noise at reduced speed can be of significant interest to utilities. Unit 1 at Seminole was not an ideal unit for a fan noise study because the two adjacent operating units eliminated the possibility of noise measurements on three sides of Unit 1. On the fourth side of the unit there was a building which caused reflections that affected the measurements. With these limitations it was still possible to record a drop in sound level from 90 db to 84 db at a location 10 feet from one of the fans with a speed change from 900 rpm to 660 rpm. This is a 50% reduction in noise and even a greater reduction in terms of perceived noise by the human ear. Fan noise and perceived noise are discussed in Appendix E.

Coupled with power savings, fan noise reduction can be an important consideration in selecting an ASD for a power plant fan application.

SENSITIVITY OF FLOW VS MW INPUT: ASCON II

The nonagreement between calculated power savings and measured power savings at Oklahoma Gas & Electric demonstrate the importance of accurate inputs to the ASCON II computer program for calculating the economics of potential ASD installations. In fact, the flow vs megawatt input is one of the most important inputs to the program because it provides the flow basis for the pressure, horsepower, and speed calculations that follow. While accuracy is desirable for all the other inputs such as heat rate vs load, fan pressure vs flow, brake horsepower vs flow, and flow vs head (system resistance), the flow vs MW is the most critical input for overall program accuracy.

If tested flow vs MW data is not available from the power plant, a reading of motor current should be obtained. Flow can be estimated from the fan or pump curve of brake horsepower vs flow after the motor current is converted to motor horsepower. ASCON II will be available from Electric Power Software Center in the fall of 1990.

10. Topics to Consider for Further Study

Section 10

TOPICS TO CONSIDER FOR FURTHER STUDY

In the course of conducting these field tests and related ASD activities, a number of questions have arisen for which it has not yet been possible to obtain the answers. Several of these items that may need further study are listed here.

IMPROVED HEAT RATE AND PLANT CAPACITY

This series of field tests has shown that ASDs can improve the heat rate of generating units and in some cases, where pumps or fans are being throttled at full unit rating, ASDs can increase plant capacity without an increase in emissions. This is an important finding in view of the recent world-wide concern for the environment.

Nearly all proposals for programs to reduce atmospheric heating (the greenhouse effect) include maximum conservation of energy and more efficient usage of existing generation facilities.

The use of ASDs to improve the efficiency of power plants and to extend the capacity of power plants as verified in this study suggest that follow-up work should be done to quantify what can be done in the U.S. to improve the environment by applying ASDs to generating units:

- Estimated SO_2 reduction from using ASDs in fossil units
- Estimated NO_2 reduction from using ASDs in fossil units
- Estimated capacity increase in fossil and nuclear units from using ASDs on largest motors

SMALL ASDS FOR POWER PLANTS

This field test program has provided valuable information on the technology that is available for large induction motor ASDs for power plants. This work has been carried out on retrofits, but certainly will impact the design of new power plants. It is suggested that a study be made on retrofitting small motors (5 to 200 hp) in power plants to determine the impact of this technology on the design and efficiency of new power plants. For instance, the conventional motor control

center may be replaced with a single large rectifier, a single large dc link capacitor and numerous transistor type voltage source PWM inverters, one for each motor. Of interest would be fuel cost savings, control equipment cost offsets and identification of motors that could benefit from ASDs.

Since the total MW of small motors in a power plant do not match that of a single large FD Fan, the power savings from using ASD control on all small motors will not match the savings on a single large fan. The savings are however significant. Considering the cost per Kw of $1200/Kw for a fossil fueled power plant, a savings of 2000 Kw for the aggregate of small motors in a 1300 MW unit would result in $2.4 million in capital cost reduction.

Also, the concepts used in motor control for small motors in industry and in utility power plants are 40 years old. It is time to look at the impact of valveless control systems for industrial and utility power systems.

Valveless control systems offer not only energy savings but improved precision of control and better means for integrating the control system into the distributed process control system of the plant. This study would also identify possible capital savings of reduced piping, reduced cable and conduit, and elimination of control valve.

DETERMINATION OF SYSTEM HARMONIC LEVEL

Present practice for determining harmonic levels on the utility bus is for the ASD manufacturer to perform a harmonic analysis of the ASD installation. It would be preferable for the utility application engineer to have the use of a simple, user friendly PC program to perform the analysis. This would allow him to investigate different input transformer configurations and explore the effects of adding ASDs to other motors on the bus at a later date. Such a program would also be useful for analyzing the effects of installing low horsepower, low voltage ASDs at the motor control center level (5 to 200 hp). Also, for instance, such an analysis could determine to what horsepower level can the Tracy 6-pulse input arrangement be taken without exceeding 3% THD V. A 2000 hp motor was tested at Tracy. Could the Tracy unit tolerate a 3000 hp motor without exceeding 3% THD.

When this project was conducted in 1986, the ASD manufacturer made the 6-pulse vs 12-pulse decision and no sensitivity analysis was offered at that time on the effect of any larger horsepower ASD ratings on voltage distortion.

LIMITS OF THD(I)

From the results of these tests, it was seen that these current-source type inverters can have low voltage THD. A diverse set of current THD values were seen. Some analytic effort should be made to determine what level of current THD would cause problems for motors, at full load and at part load.

SYNCHRONOUS MOTORS VS INDUCTION MOTORS

Some manufacturers have been able to establish the concept with utility engineers that for new power plant installations and for retrofits that require new motors, the synchronous motor with load commutated inverter is preferable to the induction motor with self-commutated inverter because of the better efficiency of the synchronous motor as compared to the induction motor.

The induction motor, with no insulated rotor components and no excitation system, has been traditionally used in power plants because of its simple construction, low cost, and record of reliability. Because of the more complex insulated rotor construction, it is questionable that the synchronous motor, with the additional exciter and voltage regulator components plus the possibilities for rotor shorts and grounds, would have comparable reliability to the induction motor, particularly in the often hot, dusty or wet environment of a coal fired power plant.

To put this question of which motor to select in perspective, a study should be made comparing the cost, efficiency, relative reliability, and range of horsepower and speed available of synchronous motors and induction motors with ASDs.

INDUCTION MOTOR NOISE AND VIBRATION

Constant speed induction motors are designed with the number of stator slots and rotor slots carefully selected to avoid core and frame vibration produced by slot harmonics. The selection of stator slots and rotor slots is largely based on experience, although there is some mathematical basis available to evaluate induction motor produced harmonics.

With the application of the ASD to the induction motor a new set of harmonics are applied to the motor that can generate core and frame vibration in place of the slot harmonics that were carefully designed out of the motor.

It would be beneficial to the application engineer to have a means of defining which harmonics excite core and frame resonance and consequently should be avoided in the ASD output.

TORSIONAL VIBRATION ANALYSIS

The average engineer working with the application of ASDs to large motors does not have a clear understanding of torsional vibration other than to know it is of concern and can result in broken shafts. A study discussing torsional resonance in induction and synchronous motors with high inertia loads would be beneficial to application engineers. Significant areas for research are:

- Basics for torsional resonance calculations
- Understanding the Campbell diagram
- Typical motor shaft capability and allowable harmonic levels
- Differences between induction motor and synchronous motors as related to torsional vibration
- Impact of application of damping couplings

FAN NOISE REDUCTION

The noise tests on the Seminole Unit 1 FD fans demonstrated that fan noise reduction can be achieved with ASDs. This particular site was not suitable to quantify the reduction because of the noise from adjacent units. A search should be made for another FD fan installation, preferably a single unit with extended unobstructed space around the unit. For such a site noise reduction data could be obtained at little cost that would be valuable to the industry in view of urban population growth near existing power plants.

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Section 11

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OTHER SUGGESTED READING

Electric Power Research Institute Publications on ASDs

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2. Electronic Adjustable Speed Drives, EU1004

3. Electronic Adjustable Speed Drives For Boiler Feed Pumps, FS5414B/D/E

4. Applications of Adjustable Speed Drives, EU.2018

Appendix A

FIELD MEASUREMENTS

Appendix A

FIELD MEASUREMENTS

As part of the detailed engineering work of this project, a coast-down test was conducted on the motor and pump or fan. The vibration amplitude and frequency were recorded as the motor and driven equipment coasted down after being tripped at full speed. The data was evaluated to determine if there were any serious mechanical resonances in the system that are a function of speed. If a serious resonance frequency existed that is excited at a particular rotating speed, operation at that speed would be avoided. The vibration measurements were taken with a real-time spectrum analyzer.

For electrical measurements to verify performance, volts, amps and watts at the input and output of the power converter were needed. When using conventional meters, it is difficult to know if the readings are correct because the operator of the metering equipment has no way of knowing of the provisions, if any, that the meter manufacturer has made in his equipment for distorted current and voltage wave forms.

To solve this metering problem, the same apparatus that was used for the vibration measurements was used to record electrical quantities. This equipment is as follows and it was connected as shown schematically in Figure A-1:

- HP5423A Structural Dynamics Analyzer
- HP54470B Digital Filter
- HP54410A Analog/Digital Converter
- HP7275A Plotter
- Oscilloscope
- Cassette Data Recorder

These devices operate at a low signal level in the range of a few volts. A current transducer was used in the CT circuit and a voltage transducer was used in the PT circuit to obtain the proper voltage levels.

After discussions with manufacturers of current and potential transformers and with electric utility personnel experienced in site harmonic measurements, it was

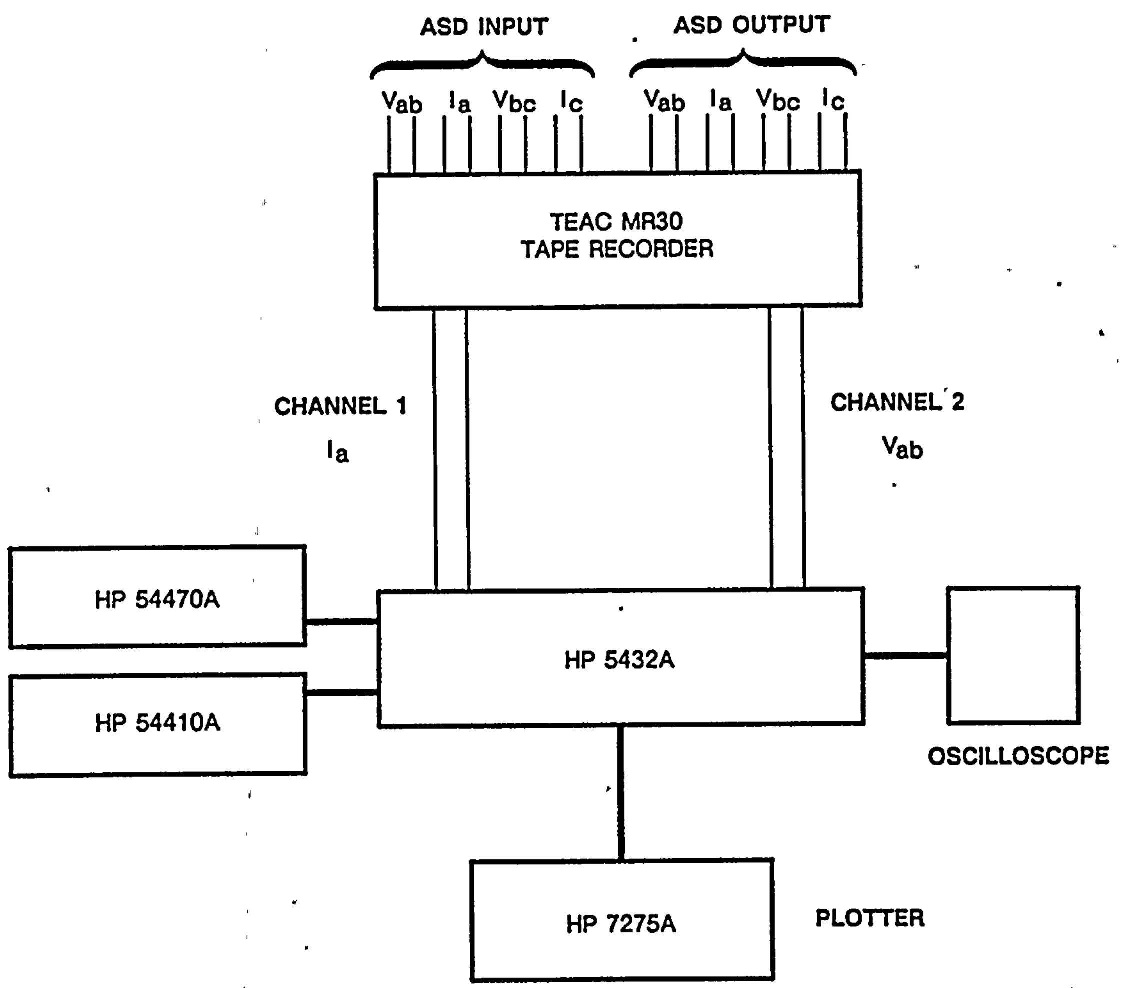

Figure A-1

EQUIPMENT FOR MEASURING
ASD INPUT AND OUTPUT ELECTRICAL QUANTITIES

decided that the current and potential transformers in the power plant switchgear were suitable for these measurements. While the frequency of the harmonics is higher than the rated frequency for these devices, the amplitudes of the voltages encountered in these tests were low enough that core saturation effects would not be a factor.

POWER MEASUREMENT

The two wattmeter method was used to measure power. With the motor operating at constant load, first one set of readings was taken at the 4 kV switchgear for the input to the ASD, the voltage between Phases A and B and current in phase A. Then another set taken of voltage between phases B and C along with the current in Phase C. Then, another set of similar readings were taken at the output of the ASD at a point in the circuit past any output transformer or filter. It is realized that this is not as accurate as measuring all three phases simultaneously at input and output, but if using only one set of measuring equipment it provides a good approximation when the load is maintained constant.

To determine power, the real-time spectrum analyzer can be used in two ways as follows:

FUNDAMENTAL QUANTITIES AND HARMONIC QUANTITIES

The current and voltage wave forms as shown in Figure A-2 for Ft. Churchill can be broken down with the fast Fourier Transform feature of the analyzer into the fundamental and harmonic components as shown in Figure A-3. The fundamental components of current and voltage produce useful torque and harmonic components produce torques which tend to cancel since some are forward rotating and some backward rotating. Where matching harmonic pairs exist, such as a 5th harmonic current and a 5th harmonic voltage power losses occur. Power can be calculated as in the following example with the two wattmeter system measurements:

$$P_A = V_1 I_1 \cos\theta_1 + V_2 I_2 \cos\theta_2 + V_3 I_3 \cos\theta_3 + \ldots + V_N I_N \cos\theta_N$$

$$P_B = V_1 I_1 \cos\theta_1 + V_2 I_2 \cos\theta_2 + V_3 I_3 \cos\theta_3 + \ldots + V_N I_N \cos\theta_N$$

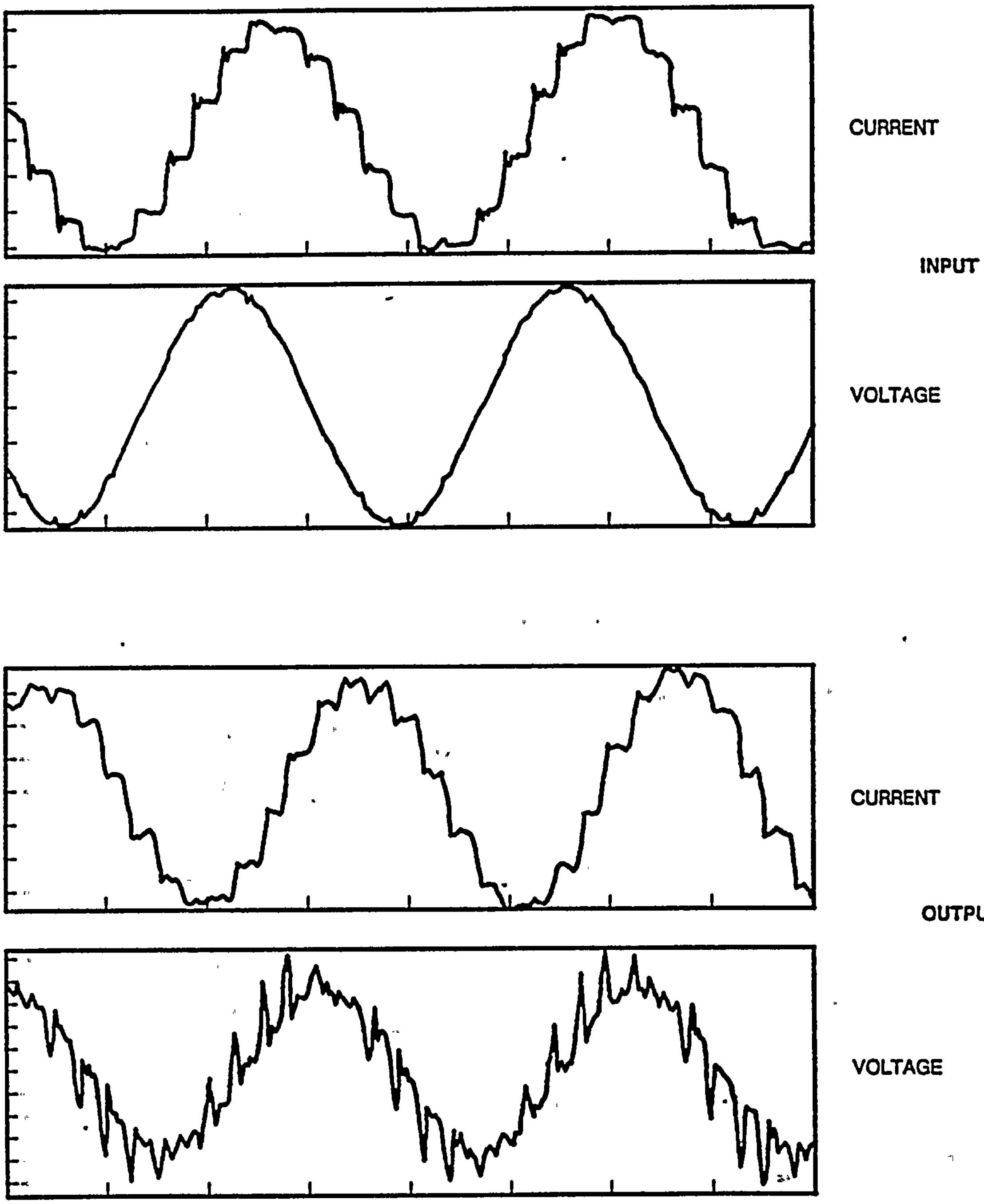

Figure A-2
12-PULSE CURRENT SOURCE ASD

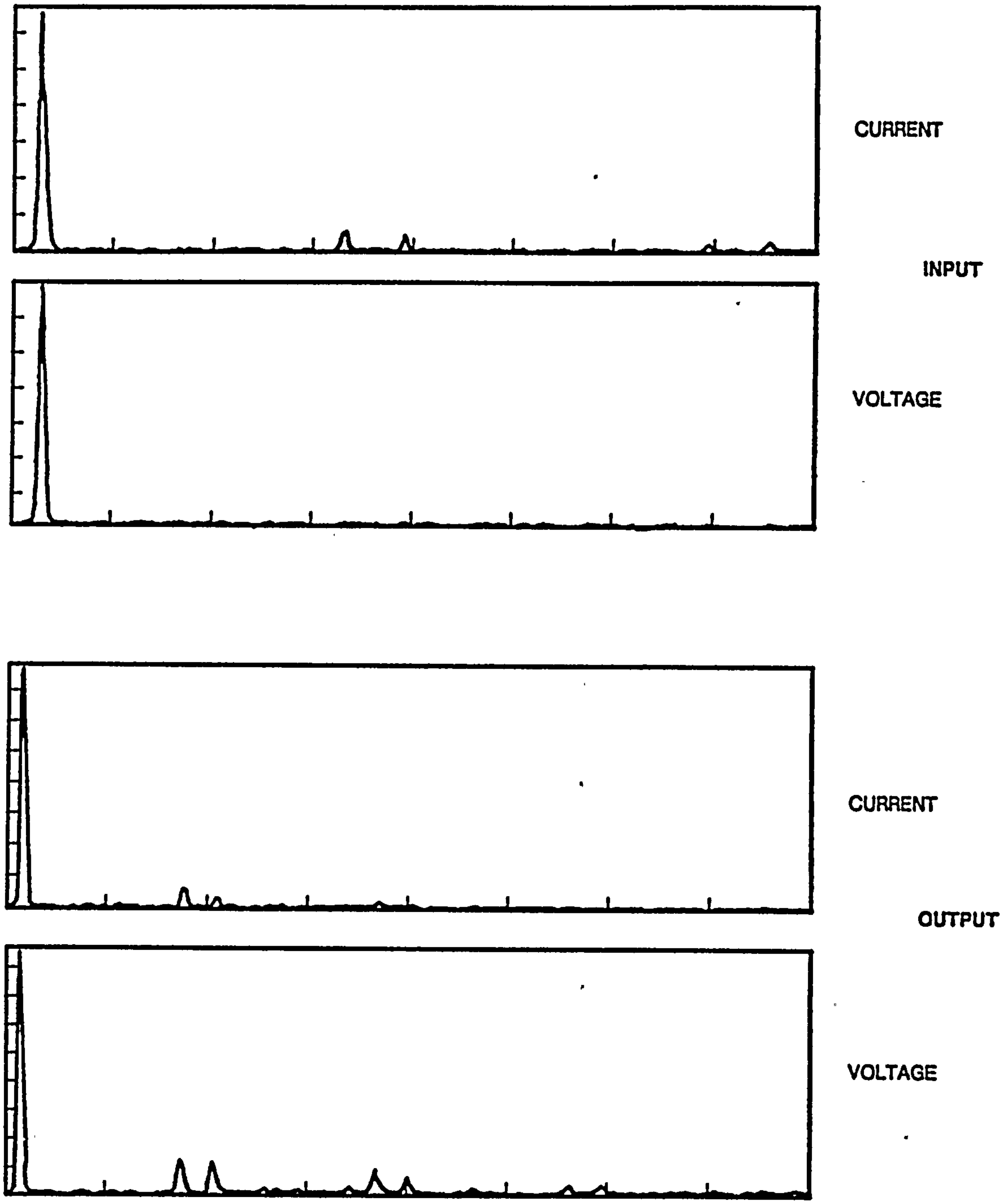

Figure A-3

CURRENT SOURCE INVERTER
12-PULSE INPUT, 12-PULSE OUTPUT
FOURIER ANALYSIS OF INPUT AND OUTPUT (30 HZ)

Total Power = $P_A + P_B$.

INTEGRATION OF CURRENT AND VOLTAGE

Alternatively, power can be determined by multiplying current by voltage, separating real and imaginary components, integrating the real or watt component with respect to time and taking the energy per second or slope of the curve as power. This can be done with the real-time structural dynamics analyzer as shown in Figure A-4 and Figure A-5, again, taking the sum of the two wattmeters. Analytical verification of this method is developed.

The real-time spectrum analyzers have the capability to record current and voltage wave shapes as shown in Figure A-2, multiply them together as in Figure A-4, and separate real and imaginary components (watts and vars). Figure A-5 shows the integral of watts or watt-seconds as a function of time. The slope of this wave, or derivative, is watts. In the following example to verify this procedure, current and voltage are assumed to be in phase for simplicity. If voltage and current were not in phase, the real power expression derived will be the same except with terms including cos 0.

The instantaneous voltages and currents are as follows:

$$e(t) = V_{M1} \cos \omega_1 t + V_{M2} \cos \omega_2 t + V_{M3} \cos \omega_3 t + \ldots \tag{1}$$

$$i(t) = I_{M1} \cos \omega_1 t + I_{M2} \cos \omega_2 t + I_{M3} \cos \omega_3 t + \ldots \tag{2}$$

The instantaneous power will then be as follows:

$$p = VI = V_{M1} I_{M1} \cos^2 \omega_1 + V_{M2} I_{M2} \cos^2 \omega_2 t + V_{M3} I_{M3} \cos^2 \omega_3 + \ldots$$

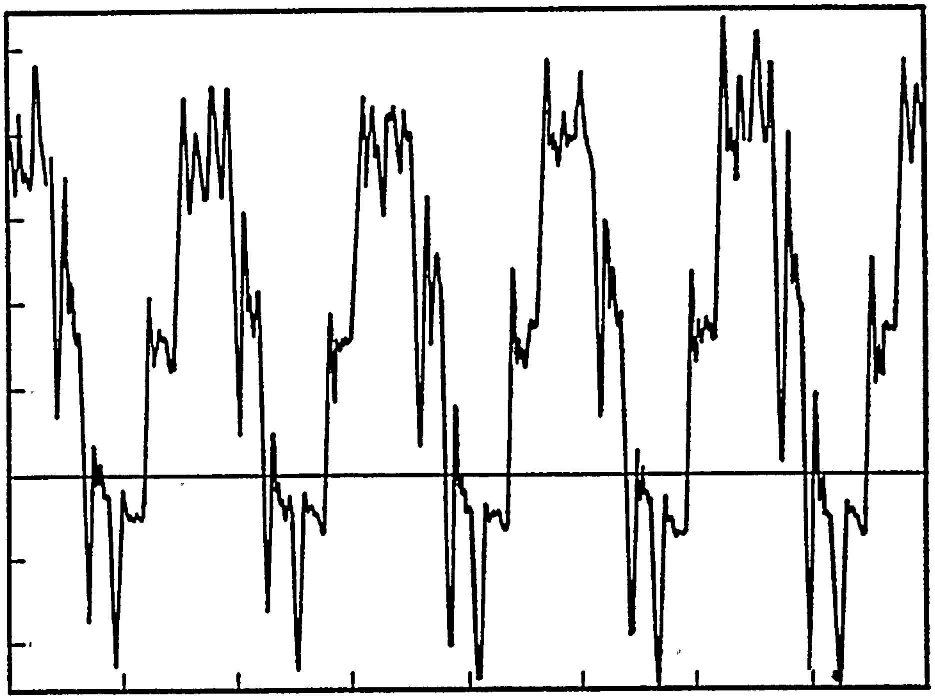

Figure A-4

VOLTS TIMES AMPS FOR 12-PULSE OUTPUT
CURRENT SOURCE INVERTER (30 HZ)

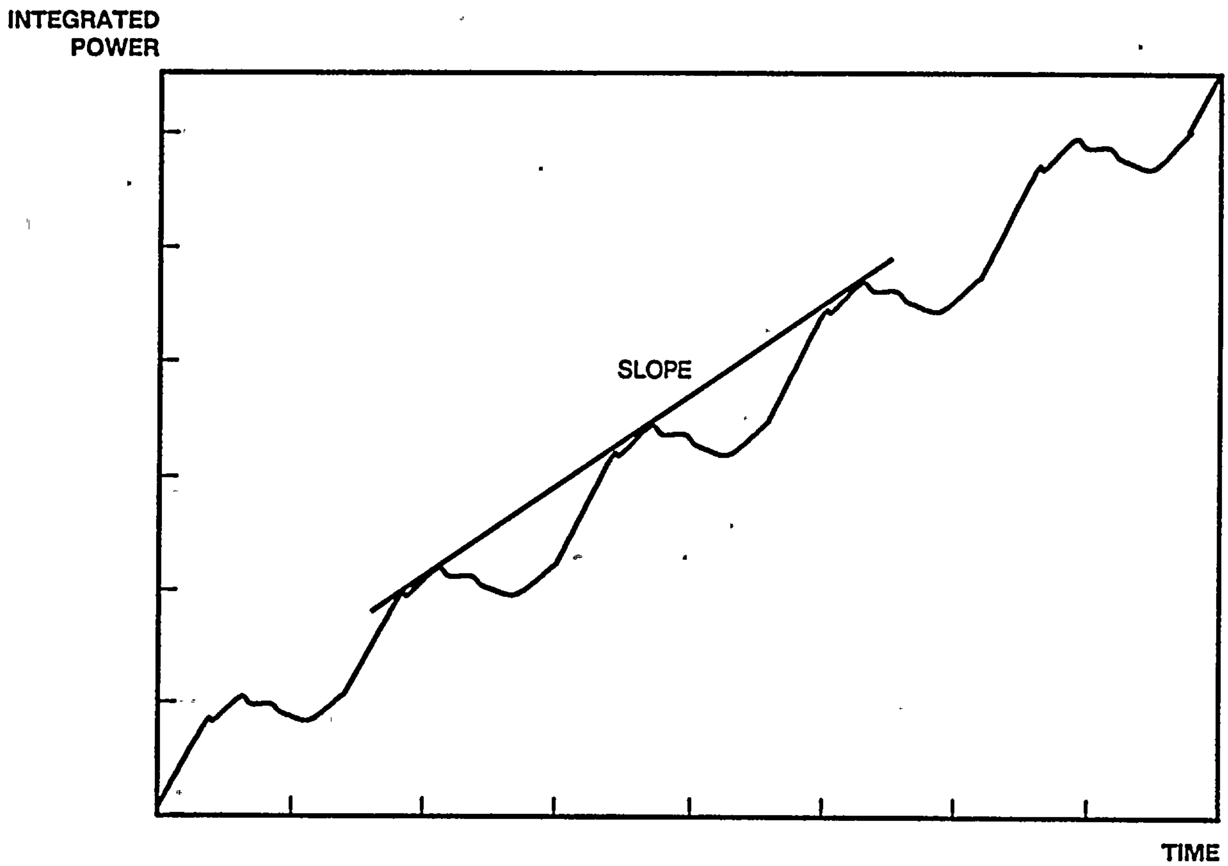

Figure A-5

12-PULSE CURRENT SOURCE INVERTER
∫ Vidt

Energy as a function of time will be the integral of the instantaneous power:

$$E = \int_0^t e(t)\ i(t)\ dt = V_{M1}\ I_{M1} \int_0^t \cos^2 \omega_1 t\ dt$$

$$+ V_{M2}\ I_{M2} \int_0^t \cos^2 \omega_2 t\ dt$$

$$+ V_{M3}\ I_{M3} \int_0^t \cos^2 \omega_3 t\ dt \qquad (4)$$

Since

$$\cos 2x = \cos^2 x - \sin^2 x = 1 - 2 \sin^2 x \quad , \qquad (5)$$

Then

$$\cos^2 \omega t = \frac{1+\cos 2\omega t}{2} \qquad (6)$$

Substituting in equation (4),

$$E_1 = V_{M1}\ I_{M1} \int_0^t \frac{1+\cos 2\omega_1 t}{2}\ dt$$

$$= \frac{V_{M1}\ I_{M1}}{2} \left[\int_0^t dt + \int_0^t \cos 2\omega_1 t\ dt \right]$$

$$= \frac{V_{M1}\ I_{M1}}{2} \left[t + \left[\frac{1}{2\omega_1} \sin 2\omega_1 t \right]_0^t \right]$$

$$= \frac{V_{M1}\ I_{M1}}{2} \left[t + \frac{1}{2\omega_1} \sin 2\omega_1 t \right] \qquad (7)$$

likewise, for the second term,

$$E_2 = V_{M2}\ I_{M2} \left[t + \frac{1}{2\omega_2} \sin 2\omega_2 t \right] \quad (8)$$

The total instantaneous energy for the fundamental and harmonic quantities will be

$$E = \sum_{i=1}^{N} \frac{V_{M(i)}\ I_{M(i)}}{2} \left[t + \frac{1}{2\omega(i)} \sin 2\omega(i)t \right] \quad (9)$$

When plotted, this equation takes the form of the curve shown in Figure A-5.

The average energy will be

$$E_{ave} = \sum_{i=1}^{N} \frac{V_{M(i)}\ I_{M(i)}}{2}\ t \quad (10)$$

Power is then $\frac{dE}{dt}$ or the slope of the curve of Figure A-5.

Appendix B

HOW TO IMPLEMENT A SUCCESSFUL UTILITY ASD RETROFIT

Appendix B

HOW TO IMPLEMENT A SUCCESSFUL UTILITY ASD RETROFIT

The ASD Field Test Program (RP-2951-6) has engineered, tested and studied seven ASDs at five electric utilities that were installed on large utility power plant motors. These installations demonstrated differing versions of three separate inverter technologies and were for both pumps and fans. The motor horsepower ranged from 1750 HP to 7000 HP.

Working closely with the electric utility and the manufacturer for each of these installations has led to a systematic approach for each retrofit that will guarantee the success of the project.

The following seven steps, if carried out with attention to detail, will assure a profitable installation, usually with greatly improved operating performance of the motor, fan or pump, and generating unit.

These seven steps are as follows and are discussed in this Appendix:

- Preliminary Study for Retrofit Economics
- Detailed Analysis and Budget Preparation
- Budget Approval
- Design Engineering
- Installation
- Startup
- Post-Startup Tests for ASD Evaluation

1. PRELIMINARY STUDY FOR RETROFIT ECONOMICS

This first step relies on the use of the ASCON II computer program to determine the fuel cost savings that can be expected by converting power plant pumps or fans from fixed speed operation to adjustable speed operation. The following information is needed to set up the program.

Annual Load Duration Curve

This is your best projection of gross power output (net power and auxiliary power) versus hours of operation for a year. ASD retrofit economics are more sensitive to load duration curve than to fuel cost or ASD cost.

Tested Heat Rate Versus Load

This information is usually available from the utility. It is an important input factor because the unit uses more fuel per kwhr of generation at low loads than at rated conditions.

Tested Fan Flow or Pump Flow Versus Load

This information is vital for the accuracy of the calculation. It can be determined roughly from a motor horsepower estimate from motor amperes, if there is no detailed flow test data.

Fan Curve or Pump Curve with System Resistance

The fan or pump curve is the manufacturers flow v. head and efficiency characteristic for a given piece of equipment. The system resistance should be updated information including the effects of any modifications that may have occurred since original installation. Fan or pump curves should be verified with the fan or pump manufacturer.

Heat Balance Diagram at Several Loads

This diagram is useful for developing input data for pump studies that is not available otherwise.

Economic Data

To convert energy savings to fuel cost and to determine the present worth of the cost and of the savings for the remaining life of the plant, the following is needed:

- Fuel Cost
- Fuel Escalation Rate
- Annual Interest Rate
- Annual Fixed Charge Rate
- Remaining Life of Plant

With this input data ASCON II calculates the fuel cost savings for each point of the load duration curve, it totals the savings and compares the present worth of the savings to the present worth of the installed cost.

By varying certain inputs it is possible to evaluate changes in capacity factor or load curve, changes in fuel cost, changes in ASD cost, etc. With this technique it is possible to bracket the fuel cost savings for best case and worst case scenarios.

This first step is important since it determines if there are sound economics in the retrofit. If the economics are attractive, proceed to the remaining steps.

2. DETAILED ANALYSIS AND BUDGET PREPARATION

The second step lays out the engineering plan for the ASD installation. The purpose of Step 2 is to develop a realistic cost estimate for the project. This will be the basis for the budget item that will need to be prepared for management approval of the project.

Considerations for the cost estimate are as follows:

ASD Equipment Rating

This is a fundamental determination that requires some investigation and study. The ASCON II calculation provides horsepower and rpm for each MW load point. With accurate input data for ASCON II, this information can be used to determine the ASD rating. The ASCON II output should be reviewed with plant operating engineers to see if their knowledge of the horsepower requirements under different operating conditions.agrees with the ASCON II calculations. If it doesn't agree, find out why.

For greatly oversized pumps and fans it is not necessary to match the ASD rating to the motor or fan rating. For undersized pumps and fans consideration should be given to operating the equipment at overspeed to obtain more flow. This may require an ASD that is rated at a higher horsepower and frequency than the motor.

For pumps or fans that operate for extended periods at low load or which shut down every night, a small ASD can provide good economics by providing adjustable speed operation at low load and returning to vane or valve control at high loads.

Harmonic Analysis

The ASD manufacturer usually is agreeable to performing a harmonic analysis of your system to determine if a 6-pulse or 12-pulse rectifier is needed. The 12-pulse rectifier uses an input transformer to provide a 30° phase shift between two rectifiers. The result is the elimination of the 5th and 7th harmonics in the currents and voltages supplying the ASD. The elimination of these harmonics is a decided benefit since they are the most powerful harmonics produced by ASDs. The input transformer also has a benefit of providing electrical isolation of the ASD from the auxiliary power system which can shield transient switching voltages from entering the ASD. Transient voltages can effect the control logic of the ASD and cause spurious shutdowns. The 6-pulse rectifier also generally requires an input transformer.

It is well established that the isolation transformer and system grounding is needed to maintain motor line-to-ground voltages at nominal values. ASDs without the isolation transformer can develop line-to-ground voltages at the motor of twice rated voltage and motor winding failures have been experienced from this over-voltage. This phenomenon is discussed in Reference 7.

ASD Enclosure and Cooling Systems

ASDs have derived from dc drives used in steel mills and offshore drill rigs. Based on the manufacturers experience, these may be air cooled or water cooled depending on industry preference. The most economic system in terms of installed cost, for a power plant ASD retrofit, will be a water-cooled ASD in a NEMA 12 enclosure. This has no extra enclosure cost or air conditioning capital cost or operating cost. This enclosure is not currently available.

Available systems have a factory fabricated air conditioned enclosure, a factory fabricated enclosure with water cooled rectifier and inverter, but with air conditioning needed for the control cubicle. Alternatively is a custom fabricated enclosure with air handling, air conditioning or water cooling units. The latter houses are factory prefabricated, modular houses which can be assembled with 4-foot panels on site.

When available, water cooled thyristors provide the best cooling system for power plant ASDs. The auxiliary pumps, filters, heat exchangers and deionizers are more reliable than air conditioning systems.

For installations where ASDs can be installed inside the plant in clean switchgear type rooms, NEMA 1 enclosures can be used with disposable furnace type filters. This scheme has the simplest cooling system of all, with only fans to cool the thyristors.

With any of these systems, power plant operators require redundant pumps, fans or air conditioners.

Extent of Electric Power Cable Requirements

If the ASD can be located close to the motor or close to the switchgear, the cable costs will be minimized. In some cases, this is not practical and the ASD may have to be located in an area remote from either. The ASD location will have an effect on cable costs. Cable costs become significant for the larger ASDs. The 7000 HP ASD pump installation used 4-500 MCM cables per phase for the 2000 volt transformer secondary connections.

ASD Location

High horsepower ASDs have significant space requirements as shown in the isometric diagrams that accompany these test results. It may not always be possible to locate the ASDs near the motor or the switchgear as was the case at IPS. Long cable runs may not be avoided, but still the installation can provide good economics.

Control System Integration

The integration of the ASD controls into the existing boiler control system needs some careful attention for the success of the project but it is not usually a capital intensive item. Consideration should be given to the adequacy of existing boiler control range, effect of ASD on turbine run-back systems, boiler implosion protection, availability of devices to match obsolete boiler control systems, pump or fan run-out limits and integration of the ASD into the plant computer control system.

3. BUDGET APPROVAL

This is usually the turning point of the project. Despite quick payback and excellent life cycle return on investment, the project may not receive approval to proceed. The reasons for disapproval may be general or specific. Inadequate cash flow can lead to rejection of a project proposal. Inability of management to

understand the concept or a distrust of new "untried" technology (power electronics) can cause the project to fail. This is a time for careful planning. Potential approaches include bringing in experts in to address particular issues that cause concern for management.

It is very important that all in-house questions and concerns be identified. Once identified, they can be addressed.

Remember the following: ASDs are reliable. They improve motor operation. They improve operation of the unit. They eliminate valve and vane maintenance costs. They increase the life of transformers and switchgear.

4. ENGINEERING

After budget approval has been secured, engineering of the project follows. This should follow the design already determined in Step 2, Detailed Analysis.

The engineering should consist of the following items:

- Preparation of ASD Specification
- Evaluation of bids
- Conduct a coast down test to determine mechanical resonances vs speed
- Purchase the ASD considering:

  --harmonics to system and to motor

  --extended warranty

  --spare parts

  --enclosure

  --defined scope of supply

  --redundancy of components

  --overload capability
- Drawing should show:

  --ASD location

  --cable

  --by-pass provision

--control system integration

--bills of material

5. INSTALLATION

To obtain the fuel cost savings promptly and achieve the calculated payback, it is important that the installation proceed posthaste, on schedule and without delay. An experienced contractor or A/E firm is invaluable at this step. It should be possible to install an ASD in one month or less, depending on the complexity of the installation. Installation plans should reflect a quick installation. For example, with a 2-year payback, one year should not be lost because of inadequate installation planning.

6. STARTUP

Startup is usually prearranged in the purchase price of the ASD. Startup consists of a detailed, step-by-step check out of all circuits by a factory trained field service engineer employed by the manufacturer. Typically, he assumes that nothing has been installed properly nor received in good condition. He checks out everything with a detailed checklist and determines that phasing is correct, insulation levels are proper, and factory supplied equipment operates as designed. Once it is determined that everything has been built properly and installed properly, he then operates the equipment on a planned, step-by-step basis. With proper installation and high quality equipment from the factory, startup can take from one to two weeks.

7. POST-STARTUP TESTING

Post-startup testing consists of operating the motor in a fixed speed mode to determine power requirements at several load points approximating the load duration curve points in the original analysis and again with the ASD in an adjustable speed mode at the same load points to determine power requirements. The object of these tests is to verify the power savings with ASD operation.

Special equipment is available to meter power circuits where harmonics are present (as they normally are with ASDs).

Utilities should measure heat rate vs load with and without the ASD to verify heat rate improvement.

CONCLUSION

With this straightforward strategy, the utility can determine the following:

- Is the ASD retrofit economic? Is it a good deal for my company?
- What does the ASD installation really cost? What are the economic benefits?
- How to design the installation intelligently.
- How to install the ASD quickly, to speedily obtain the benefits.
- Start up the ASD with a planned program.
- Verify that the ASD achieved the estimated savings.

Appendix C

HOW TO CALCULATE THE BENEFITS

Appendix C

HOW TO CALCULATE THE BENEFITS

BACKGROUND

For clarification and understanding of the calculation of the benefit of using ASDs the following is presented from Sierra Pacific's experiences. The purpose of the boiler feed pump motor ASD retrofit at the gas fired Sierra Pacific Power Co. Ft. Churchill Plant was two-fold:

- Reduce the minimum load on this spinning reserve unit, replacing the energy saved with lower cost energy
- Improve the efficiency of the unit at minimum load.

These goals were accomplished by installing a 2000 HP adjustable speed drive (ASD) on one of the 2-1750 HP boiler feed pump motors and operating the boiler and turbine at the 700 psi level rather than at the 1800 psi level whenever the unit is operated at minimum load. Figure 3-4 (Section 3) shows the unit schematically. The ASD replaces a throttling valve, Figure 3-2 (Section 3), for controlling boiler pressure and flow, saving 0.7 MW of auxiliary power, and the unit now is capable of lower load operation in a more efficient manner at the lower pressure.

Since the unit operates for long periods of time at minimum load, this conversion to low pressure operation produces considerable fuel cost savings.

This section describes how engineers at Sierra Pacific Power Company determined the fuel cost savings after the conversion.

The total annual savings were obtained by determining the following costs:

- Cost of operating the unit before the conversion
- Cost of operating the unit after the conversion
- Cost of cheaper replacement energy.

CALCULATION OF OPERATING COST

Heat Rate

To determine heat rate (Btu of fuel consumed per kwhr of energy produced), Sierra Pacific Power Co. engineers evaluated power production records and fuel gas purchase records for several months prior to the retrofit and found a consistent pattern. This was typified by a 27 day, 24 hour per day operating run in May, 1984, at an average net generation of 15.8 MW. Power production for this period was 10,401,512 kwhr with a fuel consumption of 1,552,512 x 105 Btu for a heat rate of 14,926 Btu/kwhr.

Similarly, after the retrofit, for a 61.5 day operating run through October and November 1985 at 11.9 MW average net generation, 17,484,500 kwhr of electricity was produced with 2,129,715 x 105 Btu for a heat rate of 12,180 Btu/kwhr.

Annual Operating Cost

After determining the heat rate for the two periods, the cost of operating the plant was determined by knowing the price of the heating content of the fuel, the hours operated per year and the MW output of the unit:

Annual cost = (MW net) x (heat rate) x ($ /Btu) x (Operating hours)

Thus, the cost of operating the plant before obtaining the benefits of lower minimum load and lower heat rate were obtained from

Annual cost old = (Old MW min) x (old heat rate) x (hours/year) ($/Btu)

The cost of operating the plant after conversion is

Annual cost new = (New MW min) x (new heat rate) x (hours/year) x ($/Btu)

Replacement Power

The average cost of replacement power was a known $22.70/mw-hr. value based on power production costs and power purchase costs.

The cost of replacement power is

Cost R. P. = (Old MW min. - New MW min.) x (hours/year) x ($/MWhr)

Total Cost Savings

The total annual cost savings are:

Savings total = (Cost old) - (Cost new) + (Cost R. P.)

Savings From Reduced Load

The total savings that resulted from the reduction in minimum load were obtained from the amount of the MW reduction, times the operating hours, times the cost of fuel, times the old heat rate. From this was subtracted the cost of replacement power. Thus,

Savings M.L. = (Old MW min. - new MW min.) x (hours/year) x
($/Btu) x (old heat rate) - Cost R.P.

Savings From Lower Heat Rates

The part of total savings attributable to improved operating efficiency (lower heat rate) was obtained from

Savings H.R. = (heat rate, old - heat rate, new) x (new MW min) x
(hours/year) ($/Btu)

Calculation Example

The following example is from the Ft. Churchill Field Test:

	Before ASD	After ASD
Minimum Load (Gross)	16.0 MW	12.0
Auxiliary Load	1.8 MW	1.1
Minimum Load (Net)	14.2 MW	10.9
Average Heat Rate at Min. Load	14,926	12,180
Fuel Cost, $/Therm	.39268	.39268
Hours at Minimum Load	7028	7028
Cost of Replacement Power		$22.70/MWh

Annual Cost Before Retrofit

Cost old = (old MW min) x (old heat rate) x (hours/years) ($/Btu)
= 14,200 x 14,926 x 7028 x $.39268 x 105
= $5,849,279

Annual Cost After Retrofit

Cost new = (new MW min) x (new heat rate) x (hours/years) ($/Btu)
= 10,900 x 12,180 x 7028 x $.39268 x 105
= $3,663,906

Cost R. P. = (14,200 - 10,900) x 7028 x $22.7
= $526,467

Total cost new = $3,663,906 + $526,467
= $4,190,373

Total Cost Savings

= $5,849,279 - $4,190,373 = 1,658,906

Savings From Lower Minimum Load

Savings M.L. = (14,200 - 10,900) (14,926) (7,028) ($.39268 x 10-5)
- (14,200 - 10,900) (7,028) ($22.7)
= 1,359,339 - 526,467
= $832,872

Savings from Reduced Heat Rate

Savings H.R. = (14,926 - 12,180) (10,900) (7,028) ($.39268 x 10-5)
= $826,033

This straightforward method of determining annual fuel cost savings applies to a spinning reserve type plant which has long operating periods at a fixed load. It can also be used to determine the savings at several different loads and applied to an estimated annual load curve to obtain savings for any type of unit operation.

Use of ASCON II for Automated Calculation

To calculate the benefits Bechtel has used a method based on the methodology of the ASCON II program logic. The ASCON II program calculates the horsepower required by the fan or pump with vane or valve control, then it calculates the horsepower with ASD control. This is done for each MW load on the annual load

curve. The difference in horsepower is taken and converted to kw input to the motor on vane or valve control and into the ASD for ASD control. Kilowatt-hour savings are then determined for each MW load on the annual load curve. Each kwh is converted to dollars by introducing the heat rate that corresponds to the particular MW load and the fuel cost. With test data available in the form of kw input to the motor on vane control and kw input to the ASD for ASD control, the calculation proceeds as with ASCON II utilizing the actual load curve, tested heat rate and current fuel cost.

An example of this method of determining the benefit is listed in Table C-1 based on test data from the Oklahoma Gas & Electric Seminole Unit 1 ASD test:

In this example the heat rate increments are determined by ASCON II calculation. The kw savings are taken from the tested kw savings curve of Figure 5-6. Kilowatt-hour savings and Btu savings are hand calculated.

Table C-1

DETERMINATION OF FUEL COST SAVING USING ASCON II FORMAT

MW	1985 LOAD CURVE HOURS	HEAT RATE	KW SAVINGS	$\times 10^9$ KW-HR SAVINGS	$\times 10^9$ Btu
25	22	11,688	0	0	0
75	65	11,688	0	0	0
112	46	11,688	0	0	0
137	836	11,688	150	125	1.5
162	562	11,688	600	337	3.9
187	1,838	11,494	1,000	1,838	21.5
212	953	11,138	1,400	1,334	15.6
237	1,061	10,868	1,740	1,846	21.5
262	525	10,659	1,800	945	11.0
287	473	10,495	1,240	586	6.8
312	321	10,365	1,200	385	4.5
337	212	10,261	1,130	240	2.8
362	131	10,178	960	126	1.5
387	121	10,112	800	97	1.1
412	91	10,019	571	52	.6
437	74	9,988	500	37	.4
462	64	9,965	300	19	.2
487	96	9,955	0	0	0
500	23	9,955	0	0	0

Appendix D

SAMPLE SPECIFICATION FOR MEDIUM VOLTAGE ASDS

Appendix D

SAMPLE SPECIFICATION FOR MEDIUM VOLTAGE ASDs

Specification No.

TECHNICAL SPECIFICATION
FOR
ADJUSTABLE SPEED INDUCTION MOTOR DRIVE SYSTEM

CONTENTS

CONTENTS (cont)

Page

ATTACHMENTS

Specification No.

TECHNICAL SPECIFICATION
FOR
ADJUSTABLE SPEED INDUCTION MOTOR DRIVE SYSTEM

1.0 SCOPE

A. SELLER'S RESPONSIBILITY

1. Provide all labor, materials, and tools, and perform all operations necessary for the engineering, design, fabrication, inspection, testing, documentation, delivery to the jobsite, and commissioning of a 100% solid-state adjustable-speed-drive system (ASD). The ASD shall consist of _____HP continuous output rating, _____V, 12-pulse input, electronic adjustable-speed drives, and all associated hardware and software, except as defined in this specification. Associated hardware for provision by the Seller shall include, but not be limited to, input power transformers, necessary bypass and isolation switches and disconnecting means, and associated control and protection apparatus. The adjustable-speed drive shall be a fully integrated system, compatible with motor, electricity supplied, and other system interfaces, and capable of providing the specified power requirements of the existing ______HP, _____V, _____RPM induction motor to which it is applied over that motor's rated speed and associated load range. The ASD shall be as completely factory assembled as possible within shipping and handling limitations in accordance with this specification. The adjustable-speed drive shall be installed in one weatherproof housing, suitable for outdoor service and ready for mounting on the Buyer's concrete pad. The ASD shall be fully tested at the factory prior to shipment. The outdoor pad-mounted transformers shall be located outdoors separate from the drive housing skid base.

   Information in conflict with this specification shall be brought to the attention of the Buyer. Improvements to lower cost or improve performance or reliability shall be offered as an alternate.

Comment 1:
Adjustable speed drive systems are available in 6-pulse, 12-pulse and 18-pulse arrangements. The specification is based on the 12-pulse system for the input which requires the use of an input transformer to provide two secondary windings with 30° phase shift. The ac inputs with 30° phase shift are fed to two rectifiers which may be connected in parallel or in series to the dc link. With this arrangement most of the 5th and 7th harmonics and multiples are removed from the input current to the ASD system.

The input transformer has been found to be necessary for converting 2300 volt and higher voltage motors to adjustable speed to limit the motor line to ground voltage for rectifier and inverter operation.

Comment 2:
The specification is based on ASDs located in a weatherproof, outdoor control house supplied by the ASD manufacturer. Other types of housings may be more suitable for specific ASD applications.

2. Provide truck shipment by designated truck of the assembled ASD system and all associated hardware and software to the jobsite.

3. Provide technical assistance to commission the total integrated system.

4. Provide necessary operator and maintenance training.

B. BUYER'S RESPONSIBILITY

1. Provide jobsite unloading, storage, and placement of the ASD.

2. Provide incoming and outgoing power connections to the ASD including the interconnecting power connections between the adjustable-speed drives and the input power transformers.

3. Provide the assembled ASD foundation and transformer pads and required bolts.

4. Provide the driven equipment controls interface package.

5. Provide jobsite scheduling coordination required for timely installation, checkout, start-up, operation and testing of the ASD system.

C. FOREIGN MANUFACTURERS

Any equipment not manufactured in the United States of America, no matter how insignificant, shall be tabulated by manufacturers. The quotation shall include Instruction Books, Design Ratings and a current phone number, mailing address and name of the Manufacturers Application Engineer. Foreign equipment when received and not complying with the above will be rejected.

Comment 3:
This paragraph requests information on foreign manufactured devices and may be omitted.

2.0 QUALITY STANDARDS

A. GENERAL

1. The Seller shall submit to the Buyer for his approval the applicable Quality Assurance (QA) and Quality Control (QC) policies and associated procedures.

2. The Seller shall submit to the Buyer the necessary documentation throughout the project implementation to assure the performance of applicable tasks and services stipulated in the submitted QA and QC manuals which had been approved by the Buyer.

3. The Seller shall comply with all latest editions of applicable codes and standards, but not be limited to, those referenced in this specification. Where a standard is referred to and conflicts with a part of this specification, the Buyer should be consulted in writing for immediate resolution.

4. The Seller shall provide the Buyer with certified copies of all test reports performed in accordance with required tests specified in this specification.

B. REFERENCED CODES AND STANDARDS

Sponsor		Number	Subject
ANSI	C57.13	1968	Requirements for Instrument Transformers
ANSI	Z55.1	1967	Gray Finishes for Industrial Apparatus and Equipment
ANSI	MC096.1	1975	Temperature Measurement Thermocouples
IEEE	444	1973	Standard Practice and Requirements for Thyristor Converters for Motor Drives
IEEE	519	1981	Guide for Harmonic Control and Reactive Compensation of Static Power Converters
ANSI	C34.2	1968	Standard Practices and Requirements for Semiconductor Power Rectifiers
IEEE	59	1962	Standard Semiconductor Rectifier Components
ANSI	C57.12	1980	General Requirements for Distribution, Power and Regulating Transformers
ANSI	C57.16	1971	Requirements, Terminology and Test Code for Current Limiting Reactors
ANSI	C57.18		Transformers
ANSI	C37.30	1971	Requirements for High Voltage Air Switches, Insulators and Bus Supports
ANSI	C37.20	1978	Switchgear Assemblies including Metal Enclosed Bus
NEMA	CP-1	1976	Shunt Capacitors
NEMA	SG-5	1975	Power Switchgear Assemblies
NEMA	ICS 3.1	1978	Safety Standards for Construction and Guide for Installation and Operation of Adjustable Speed Drive Systems
NEMA	C55.1	1968	Shunt Power Capacitors

Comment 4:
Standards are listed for guidance for Buyer and Seller. Either may wish to emphasize certain portions of particular standards.

3.0 SERVICE REQUIREMENTS

A. CONDITIONS OF SERVICE

Frequency converters including filtering equipment and dc link inductors or capacitors shall be furnished in factory assembled, prewired, pretested, weatherproof housing including all necessary ventilation, cooling and heating equipment required for the following environmental conditions unless otherwise stated in Attachment C.

Site	City, State
Ambient Temperature	35 to 120°F
Altitude	Sea Level
Humidity	100% Relative Humidity
Wind, (Side Wall)	30 psi
Air entrained salt, ppm	.003-.01
Solar Radiation, Btu/ft^2-hr	360
Dust micrograms/$meter^3$	.180
Rain/Wind	4 inches per hour/100 MPH
Seismic	Zone 1

Comment 5:
Service conditions will vary from site to site. Values presented here are an example.

B. DESIGN LIFE

The design life of the equipment should not be less than 35 years with nominal maintenance and repair, to be consistent with the design life of other utility generation, transmission, and distribution equipment.

Comment 6:
Nominal maintenance and repair includes keeping the ASD equipment clean, keeping cooling equipment in good operation condition and maintaining switches, transformers and reactors according to recommended practices.

4.0 OVERALL SYSTEM REQUIREMENTS

A. SELLER RESPONSIBILITY

1. The Seller shall have complete responsibility for all equipment and accessories included in this specification. The Seller shall perform the necessary analysis of the operation of the Buyers induction motor when powered by Seller's power conversion equipment to assure the following:

   a. The motor will operate in a stable manner without undue heating, vibration or noise and with adequate torque margin for the specified acceleration requirements.

      Undue vibration shall be defined as an increase of .001" (peak to peak displacement) or more in mechanical vibration on the motor bearing caps, an increase of .003" (peak to peak displacement) or more of mechanical vibration on the motor housing, or any increase in torsional vibration on the motor or fan shaft as determined by the Buyer's tests conducted with and without the ASD in service.

      Undue noise shall be defined as any measurable increase in motor noise as determined by the Buyer's tests conducted with and without the ASD in service.

      Undue heating shall be defined as additional heating which causes a stator RTD temperature rise above rated temperature rise at any motor speed up to rated speed and at any horsepower output up to rated horsepower output.

b. The ASD shall not cause the motor to operate in excess of its design limits.

c. The ASD shall not introduce sufficient harmonics into the existing power system or motors to cause misoperation, of or damage to, the motors or to other equipment. The motor data and existing system impedance data will be provided by the Buyer. Current harmonics entering the motor from the ASD shall not exceed 15% of the fundamental for any individual harmonic.

d. The motor shall satisfactorily operate over the full speed and load ranges while power is supplied from the new ASD or at constant speed from the existing ______V power source without the ASD compromising motor, related system capabilities, reliability, life expectancy, or impacting adversely existing operation and maintenance practices.

2. The total harmonic distortion from the rectifier shall not exceed 3.0 percent voltage distortion or 12.0 percent current distortion with the ASD operating. The maximum deviation of the voltage from a sine wave at the 13.8 kV bus shall not exceed 33 percent with the ASD in operation as compared to the voltage with the ASD not in service.

Comment 7:
IEEE Standard 519 suggests 5% voltage distortion as a limit for power electronic equipment connected to busses with other equipment or 8% voltage distortion for power electronic equipment on a dedicated bus. With some preliminary analysis it is often possible to specify a more conservative value as has been done in this sample.

3. The Seller shall perform a number of analyses defined in Section 8.0.

B. SCOPE OF SUPPLY

1. The Seller shall supply all the components necessary for the successful operation of the ASD, whether or not specifically

identified in this specification. Each unit shall be considered as a package which shall include, but not be limited to, the following:

a. Power and control modules (consisting of a line converter to change the ac supply to dc and a load inverter to change the dc to an adjustable frequency ac for controlling motor speed) needed for a fully-functional system.

Comment 8:
Systems other than dc link type systems are available for special applications. Cycloconverters are used for high torque, low speed applications. A new series resonant converter is under development.

b. Weatherproof house capable of containing all major components except input and output transformers.

c. Input isolation power transformers to be outdoor, oil-cooled, type OA complete with current transformers as required for transformer protection.

Comment 9:
Dry type transformers are preferred for some indoor applications.

d. Additional motor protection required by the interposition of the ASD between existing motor protective relays and the motor, such as phase unbalance, ground fault protection, etc.

e. Ancillary equipment including cooling systems.

f. Controls and instrumentation with provision for local and remote supervision and control.

g. Redundant coolant system elements with automatic control shall be supplied for both internal (drive) and external cooling (house) cooling loops.

Comment 10:
Water cooling is preferred for power plant installations and for large ASD ratings. Open circuit air cooling can be used in clean, dry environments. Air conditioning and air handling systems have been used effectively for ASD cooling.

h. Output current and voltage transformers for efficiency determination (item C-5).

Comment 11:
If analysis tests are not required, these devices can be omitted.

C. PERFORMANCE

1. The induction motors shall start and accelerate their loads as shown on the load speed-torque curves at reduced frequency and voltage to limit starting current to ___ percent or more of rated full load current. The motors shall be capable of accelerating the WK^2 of the load per Attachment B and ramping up to 105% of motor rated speed. Curves demonstrating this capability shall be submitted showing that the motor torque at the minimum voltage is above the load torque at all speeds and that the motor safe-heating limits will not be exceeded during starting under the conditions of specified maximum starting current.

Comment 12:
5% overspeed may not be needed. Current limit and acceleration rate are related. Higher acceleration rate requires a higher current limit. If acceleration rate is specified, current limit should be left to the manufacturer.

2. Motors and control equipment shall be capable of accelerating the fan by a minimum rate of 5 percent of operating speed per second in the operating speed range.

Comment 13:
5% speed/second acceleration may not be necessary. Often a lower rate is adequate. It may be necessary to specify a rate of deceleration for ID Fans.

3. The ASD shall be capable of withstanding an automatic fast bus transfer (low voltage bus time of 5 to 8 cycles) or an automatic backup bus transfer (low voltage bus time of one-half to one second). These bus transfers are between the generating unit auxiliary bus and the reserve bus. The FD Fan speed should retain pretransfer status. See Attachment E for present transfer scheme.

Comment 14:
Bus transfer schemes vary among utilities. This paragraph and Attachment E should be modified for the specific installation.

4. The maximum reactive power (KVAR) requirement at all operating load levels shall not exceed the KVAR required at rated HP.

5. 97% or better efficiency of the ASD, ac to ac is required at ____ HP rating. At 25% load, the efficiency should not fall below 90%.

6. The seller shall design the proposed ASD systems to offer the following features:

   a. Optimized harmonic generation to reduce total sine wave distortion to the extent necessary in the Buyer's power source and motor power supply, while assuring satisfactory performance without misoperation of or damage to, interfacing power plant systems. Harmonic voltages and currents introduced into the ac network shall not exceed a total harmonic distortion of 3.0 percent voltage or 12.0 percent current.

   b. Optimized ASD design to yield minimum sine wave deviation to the extent possible while assuring satisfactory performance without misoperation of or damage to, interfacing power plant systems.

Maximum deviation from sine wave at the ASD input to bus shall not exceed 33%.

c. Optimized thyristor selection to yield maximum reliability, minimum losses, maximum voltage withstand and minimum protective circuits.

d. Optimized number of thyristors and associated electronic components to yield total system cost effectiveness, maximum reliability and minimum maintenance.

e. Thyristor selection should be supported by the seller's analysis of associated desirable features and corresponding disadvantages.

<u>Comment 7</u>:
IEEE Standard 519 suggests 5% voltage distortion as a limit for power electronic equipment connected to busses with other equipment or 8% voltage distortion for power electronic equipment on a dedicated bus. With some preliminary analysis it is often possible to specify a more conservative value as has been done in this sample.

7. The ASD shall be sufficiently free of radiated and conducted EMI, RFI and TIF, so as to not result in misoperation of instrumentation and communications equipment.

8. The ASD system shall be designed to correct automatically for internally or externally generated malfunctions which could cause operation beyond its design capability. Fault current available at the feeder and interface details is specified in Attachment C.

5.0 DESIGN REQUIREMENTS - ASD SYSTEM

A. POWER CONVERSION AND CONTROL MODULES

1. The rectifier/inverter equipment shall be a coordinated assembly of freestanding NEMA Type 1 enclosures in a weather-proof housing with ancillaries including cooling and heating system. The equipment shall be capable of continuous operation at ____ HP, at _____V. Operation with output frequency from 0% of 60 HZ to 5% above 60 HZ is anticipated. With the existing ____ HP motors, drive output will be limited to ______ HP (the 1.15 service factor rating of the motors). The drive equipment shall be capable of ±10% voltage operation with occasional motor starting causing bus voltage dips to 80% voltage. The normal operating current limit of the drive is 100% based on ______ HP. The control and supervision modules shall be suitable to interface with Buyer's multiple unit supervisory and control system.

2. The input isolation transformers shall be suitable for rectifier service and shall contain no PCB fluid. Transformer impedance shall be selected to limit initial fault current to a safe value for ASD system thyristors. Oil-cooled type equipment shall be furnished.

3. The rectifier/inverter equipment shall be a 12-pulse or greater input rectifier system and 6 or 12 pulse inverter output system with provisions to minimize harmonics to the motor.

   Comment 15:
   The inverter for this specification is based on a 6-pulse system which can be based on the GTO-PWM concept, either current-source with output filter or voltage-source, or the modified load commutated inverter which also uses an output filter. Inverters may also be current-source or voltage-source systems without pulse width modulation but with 12 pulse or 18 pulse arrangements to reduce harmonics to the motor.

4. The ASD, including all power equipment peripherals such as input transformers, switches, d.c. link inductors and capacitors, etc.

shall be sized to deliver the ____ HP horsepower requirement continuously for the total fan load range with a system input voltage of ______V ±10% with occasional -20% voltage fluctuation.

5. Thyristors shall have at least a 250 percent peak repetitive voltage margin and shall not be paralleled without the proper impedance separating the two legs. Thyristors shall be fired through pulse transformers through gate power units, both initiated by their single source fiber optics. Cell stack shall be of modular design and interchangeable to facilitate replacement. Current transformer output should be accurate throughout entire speed range. The power electronics shall be of a fuseless design. All bus work shall be prefabricated and copper.

6. The electronic components in the ASD shall be protected against over-temperature as a result of loss of cooling.

7. Thyristors and/or module combination should be protected against voltage transient disturbances in the reverse and forward directions as well as against the rate of the associated transient without regard to voltage transient amplitudes.

8. The ASD modules shall be of proven design with the specified reliability. The rectifier and inverter thyristor stacks shall be so designed to normally operate at full voltage with N-1 thyristor operation in each leg of the associated bridges.

9. The printed circuit boards of the ASD modules shall be so designed that hardwired connections are minimized and remain intact when the printed circuit boards are removed.

10. The ASD shall be protected against, but not be limited to, input open circuit, output open circuit, open phase, loss of control power, loss of gating power, power supply over- and under-voltage, shorted thyristors, loss of cooling, electronic ground fault, excessive speed and overspeed indication, volts/Hz limit and high temperature.

11. Converter/inverter speed, firing and current loop control modules shall be microprocessor controlled.

Comment 16:
ASD control systems are available in both analog and microprocessor based systems. Microprocessor based systems are particularly needed with pulse-width modulation type control algorithms.

12. The control modules shall be microprocessor based digital control and shall provide the following control functions:

    a. Controlled acceleration or deceleration, separately adjustable with current limit override acceleration protection.

    b. Frequency control shall have a steady state accuracy of 0.5 percent.

    c. Separately adjustable min/max frequency limits compatible with full speed and load ranges shall be provided.

    d. Automatic control for over-frequency operation shall be restricted by the use of a selector switch.

    e. Process Follower - To accept 4-20 ma transmitter signal. A relay and terminals shall be available for switching to alternate external source.

    f. Low Frequency Start/Stop - Adjustable linear ramp up/down to required speed

    g. Current limit regulator, adjustable

    Comment 17:
    The adjustable current limit may or may not be available. It can be obtained in digital control systems by reprogramming. With analog control systems the limit may be fixed. The current

limit is not likely to be changed once an ASD is installed so this feature may not be necessary.

h. Speed regulator

i. Current and voltage feedback with isolation

j. Drive sequencing logic

k. Drive protection functions

l. Local start, stop and speed controls for field test and startup, not accessible from front of panel.

m. Coordinated safe stop on protection signal, i.e., breaker trip, boiler control.

Comment 18:
ASD control systems when integrated into power plant boilers are generally arranged to provide safe shutdown with emergency tripping of the motor breaker or tripping of the boiler or turbine.

n. LED display for semi-conductor and control monitoring

o. Digital voltmeter, motor

p. Digital ammeter, motor

q. Digital horsepower meter, motor

r. Digital speedmeter, motor.

s. Optimize the ASD design for either constant or programmed motor volts/Hz control.

t. Continuous frequency range from 0-64 Hz.

u. The drive shall be so designed to prohibit swinging from very low speed operation to starting mode of operation.

v. The drive shall be so designed to include the following control function regulators:

- speed
- current
- flux
- overvoltage
- load angle
- source minimum angle
- load phase lock loop
- source phase lock loop
- acceleration rate
- deceleration rate
- current limit

w. The drive shall be so designed to allow manual and/or automatic transfer to across-the-line operation.

13. The following signal interfaces shall be provided between the drive and other equipment:

a. 1 - Analog input channel (4 to 20 ma)
b. 3 - Analog output channels (4 to 20 ma) for speed, amps and volts
c. 6 - Contact closure inputs
d. 6 - Contact closure outputs
e. Refer to Attachment F

Comment 19:
The 0-20 ma input controls the operation of the ASD. The 3-analog outputs provide remote indication of motor amp, speed and volts. These may be remote meters or they may be fed to a computer for display on a CRT. Similarly the contact closure

outputs are ASD status alarms for remote indication on CRT or annunciator.

14. The control modules shall provide the following protection functions which will shut down the drive and be indicated by LEDs.

    a. Stator winding overcurrent
    b. Stator overvoltage
    c. Overspeed
    d. Open phase or missing gate
    e. Commutation failure
    f. Loss of cooling air
    g. Transformer over temperature
    h. Shorted thyristor leg
    i. Loss of logic control power
    j. Loss of gate power supply
    k. Speed command signal failure
    l. Overcurrent rectifier and inverter
    m. AC power supply undervoltage
    n. External trip
    o. External permissive shut down
    p. Electronic ground fault detector
    q. Stator RTD temperature

15. The following signals shall be sent from the drive to the customer's control room:

    a. Speed indicating signal
    b. Alarm signal (close on alarm)
    c. Fault signal (close on fault)
    d. Motor amperes

16. The following operator devices shall be furnished on or inside the door of the control cabinet:

    a. Fault indicating lights
    b. Alarm indicating lights

c. Reset button

d. Drive ready light

e. Horsepower indicator

f. Motor speed indication

g. Motor ammeter

h. Motor voltmeter

i. Stop push button

j. Start push button

k. Manual speed pot.

l. Local/remote selector

17. The control modules shall include the following diagnostic capabilities:

    a. Continuous on-line full coverage self diagnostics for both hardware (to the circuit board level or lower) and software.

    b. First fault indication and ability to locate subsequent system faults

    c. Ability to recall events that preceded a shutdown of system

    d. Ability to monitor major system components with status lights for replaceable elements.

    e. Diagnostic printer and modem, English language output and capability to communicate all diagnostic information to distributed process computer.

B. ISOLATION TRANSFORMERS

1. Input isolation transformers shall be 3-winding type, outdoor, oil-filled type OA, self-cooled rated 55 C rise over 50 C ambient, continuous for ANSI T1 duty class, ______ volt primary volts, 60 hertz double secondary delta and wye ungrounded for use with 12-pulse converter. The input transformers shall not be adversely affected by harmonics in the ASD input voltage and currents.

2. Input transformer impedances shall be selected to limit initial fault current to a safe value for converter thyristors. Output transformer impedances shall be selected for proper and safe motor operation.

3. The following accessories shall be provided with each transformer:

   a. Ground pad
   b. Welded or bolted cover with bolted, gasketed inspection plates
   c. Provisions for jacking and lifting
   d. Base designed for skidding or rolling in either direction
   e. Transformer shall be separate from drive skid.
   f. Connectors for incoming and outgoing power cables.

4. High voltage terminal box shall be provided with suitable bushings.

5. Two 2-1/2 percent rated kVA high voltage taps above and below rated voltage with manual tap changer for de-energized operation shall be provided on the input transformer.

6. Low voltage connection shall be metal enclosed, air filled terminal compartment.

7. Devices shall be provided to alarm the following conditions:

   a. High oil temperature
   b. Hot spot winding temperature
   c. Pressure relief
   d. Low oil level

C. CAPACITORS

Output filter capacitors shall be designed and sized for removal of remaining undesirable harmonics. Electrical resonance of the output filter capacitors and motor within the operating frequency range shall be

avoided as shall self-excitation of the motor after an ASD trip. The following guidelines apply to the filter capacitor:

1. Capacitors shall be individual single phase one or two bushing units.

2. Capacitor units shall be housed in steel hermetically sealed tanks with no PCB fluid.

3. Bushings shall be glazed wet porcelain.

4. Capacitor units shall be "all film" design.

5. Insulating fluid shall be non-PCB. Each individual capacitor shall be clearly labeled as containing NO PCB's.

6. The rated capacitor voltage shall be greater than the maximum voltage that the capacitor will be subjected to during any mode of drive operation.

7. The internal corona starting voltage or ionization level shall not be less than 150 percent of rated voltage at 25 C.

8. The temperature of the hottest spot inside the capacitor case shall not exceed 85 C when the capacitors are operated continuously at 110 percent of rated voltage.

9. Capacitor and reactor filter units shall be an integral part of the drive assembly with interconnecting bus included. All bus work supplied shall be copper with silverplated connections.

10. Means shall be provided to disconnect and ground the capacitors.

D. CONTROL PANELS

1. All panels wiring shall be drive manufacturers insulated switchboard wire 600 volt, 90 C, single conductor.

2. Terminal blocks for termination of Buyers control and low power terminals shall be rated 30 amperes, 600 volts with washer head screw type connection.

3. All power connections above 30 amperes shall be pressure (crimp) type connectors with a NEMA pad, including terminations for purchasers connections.

4. Wire connections, other than factory soldered connections, shall be made with non-insulated straight shank, crimp type, plated, ring-tongue terminals.

5. Each terminal block and each point used on terminal block shall be labeled with tape or stick on labels.

6. All circuit boards shall be accessible for quick and easy replacement without special tools.

7. Components shall be accessible through lockable hinged door.

8. No electrically-energized components shall be accessible with doors closed.

9. Hardware shall be properly designed and/or treated to resist corrosion typically produced in a seaside environment.

10. Power bus shall be conservatively rated and so designed for maximum current rating and maintenance-free operation.

11. All interconnecting wiring, equipment and terminal board points shall be properly identified using approved identification marking.

12. Modular construction shall be used to minimize maintenance and change-out required during the troubleshooting process.

13. Panel wiring termination shall be of the ring-tongue type on all terminal board connections.

14. Thermostatically controlled space heaters shall be provided.

15. All panels and equipment shall be designed to maximize safety of operating and maintenance personnel.

E. WEATHERPROOF CONTROL ROOM

The two power conversion and control equipments shall be enclosed in a weatherproof power and control room. Each power and control room shall have the following features:

1. Weatherproof enclosure with insulated steel walls.

2. Insulated, sloping steel roof, removable for access.

3. Control wiring for external signals to be terminated in a compartment accessible from the outside of the control room.

4. Base to be of rugged fabricated steel suitable to self-support the control house and to include raceways for interconnecting power cables.

5. Floor to be steel plates with rubber mats to prevent slippage and to provide personnel electrical isolation.

6. Personnel access doors at each end to have anti-panic hardware and to be of sufficient size to allow removal of largest equipment components.

7. One copper ground stud suitable for 4/0 stranded copper.

8. Motor control center to supply power to auxiliary equipment and lights. MCC to have dual feed 480V, 3-phase external supplies from utility.

9. Adequate fluorescent lighting.

10. Lifting lugs.

11. Enclosure pressurized to isolate undesirable environment.

12. 8-120V ac receptacles.

13. Thermal transmittance through metal side U=.09, roof U=.05.

14. Two 5 kw, 460V thermostatically controlled space heaters.

15. Redundant air conditioning for personnel comfort and for removal of any equipment generated heat not removed by drive equipment system.

16. The control room and all equipment shall be designed and arranged to maximize personal safety of operations and maintenance personnel.

F. MISCELLANEOUS

1. All lighting shall be designed for 120V ac

G. PAINT

1. Interior walls and ceiling shall be cleaned and primed in accordance with the Sellers standard procedure and shall have two coats of a higher grade white finish paint, each having a nominal thickness of 1 to 1.5 mils.

2. Outdoor - All ferrous metal shall be cleaned and primed per the Sellers standard procedure and shall be painted ANSI 70 gray. The paint shall be a minimum of 5 mils thick including the transformers.

H. TOOLS AND TEST EQUIPMENT

1. The supplier shall supply a complete list of testing equipment, and any special tools required to install and maintain the drive system. Price adders should be included for the supplier to supply any special tools or special testing equipment required.

6.0 SHIPPING, HANDLING, AND STORAGE

A. The method of preparation for shipment shall protect converters and all other parts, auxiliary devices and accessories against corrosion, dampness, breakage, or vibration injury that might be encountered in transportation and handling. The manner of packaging shall be such as to prevent tampering or pilfering and shall be acceptable to the transportation companies.

B. The units shall be delivered in the largest subassemblies practical for transportation.

C. The Seller shall provide instructions for on site storage and handling to be performed by the Buyer.

7.0 INSPECTION AND TESTING

A. SHOP TESTS

1. Power rectifier and inverter equipment to be given routine tests in accordance with IEEE 444.

2. Certified copies of all test reports shall be submitted.

3. Buyer reserves the right to witness final shop tests and shall be notified a minimum of 14 days prior to such tests.

B. FIELD TESTS

1. Seller shall demonstrate trouble free, stable operation for conditions of starting, stopping, full load, three quarter load, half load, quarter load, no load and intermediate loads.

2. Tests shall include 100 hours of operation at full load to demonstrate adequacy of equipment for thermal and voltage stresses.

3. Tests shall demonstrate 60 days of trouble free operation.

8.0 ANALYSIS

The Seller shall provide all necessary studies that support the satisfactory operation, while maintaining existing system reliability, of this project. These studies are not limited to: (1) Harmonic analysis of currents and voltages distorted by the ASD in the Buyer's electric system over the full ASD speed and load ranges; (2) Harmonic analysis of currents and voltages to the motors over the full speed and load ranges; (3) Torsional analysis of _________________ and motor machinery; (4) Motor and ______ performance and capabilities over the full speed and load ranges; (5) Failure mode and effect analysis of the supplied drive system to support any reliability analysis the Seller may choose to perform.

Comment 20:
Torsional analysis is more critical for high inertia fans than for low inertia pumps.

1. Torsional Analysis

The Seller shall perform a torsional analysis (computer simulated with written documentation of results) on the entire rotating drive system and load. The analysis shall determine the magnitude and frequencies of mechanical oscillations resulting from the electrical harmonic exciting frequencies produced at all operating speeds from 0 percent to 110 percent and all operating modes; i.e., start-up, normal operation as well as fault conditions. From the results of the torsional analysis, the necessary coupling equipment, if any, shall be specified.

2. Harmonic Analysis

The Seller shall perform a harmonic analysis to ensure the electrical system is not adversely affected and shall include inverter contributions. The analysis shall be performed for 12-pulse input operation. If the harmonic voltage distortion factor or the voltage deviation factor exceeds the specified value, the Seller shall supply and install the equipment to reduce distortion or deviation to within the above specified limits at no

cost to the Buyer. The Buyer reserves the right to terminate the purchase order, without any cost or obligation incurred by the Buyer, and the Seller will refund to the Buyer any payments made under Section 14.0 prior to such termination, if by test (a) the total harmonic distortion factor exceeds 5 percent voltage, 15% current or (b) if the voltage deviation factor exceeds 35%.

3. Motor Analysis

The Seller shall perform an analysis of the (specify manufacturer) ____________ HP Motors operating with the proposed adjustable speed drive. The analysis shall investigate the following:

a. Stator winding, stator core, rotor winding and rotor core additional temperature rise from inverter-produced harmonics.

b. Motor efficiency at 100%, 75%, 50% and 25% speed with fan load.

c. Additional motor noise at 100%, 75%, 50%, and 25% speed with fan load.

d. Capability of motor stator winding insulation system to withstand harmonic voltage.

e. Bearing heating over operating speed range.

f. Internal fan cooling over operating speed range.

g. Effect of pulsating torques and associated values, if any.

h. Effect of reverse operation during generation mode at motor terminals with the use of capacitors at such terminals.

i. Effect of rapid voltage transient at motor terminals.

4. All studies and analysis performed by the Seller shall be given to the Buyer in written reports and in oral presentations for the Buyer's approval.

9.0 WARRANTY AND AVAILABILITY GUARANTEE

If any defect in apparatus supplied, or failure to comply with this specification shall appear within the period of three (3) years from the date of final acceptance, not to exceed 39 months from delivery, the Seller shall be immediately notified, and he shall correct without delay, and at his own expense, the defect or defects or failure of compliance, by repairing the defective parts or parts, by supplying a nondefective replacement or replacements, or by correcting a defective or deficient design.

In addition, the Seller shall guarantee 99% availability of the ASD for 12 consecutive months from the date of final acceptance. The penalty for not achieving this availability record is $1,000.00 per hour up to a maximum of $100,000.00 for any downtime above 1% that is attributed to faulty operation of the ASD or to misoperation of, or damage to, the forced-draft fan motors or other plant equipment or systems caused by the ASD.

Comment 21:
Warranty and availability guarantees vary with market conditions and are subject to negotiation.

10.0 CHANGES

The Buyer may, by written Change Order, make any changes, including additions or omissions in quantities ordered, or in the specifications or drawings. If any such change affects the amount due, an equitable adjustment shall be made.

11.0 WAIVER

All modifications or revisions shall be in writing and in no way shall any purported oral modifications or revisions of the purchase order by Buyer operate as a waiver of any of the terms of this specification.

12.0 DELIVERY

Delivery of the equipment is required by (specify date) ____________. Failure to meet this delivery date shall result in the Seller paying to the Buyer liquidated damages of $1000.00 per day for each day past (specify date) ________ __________.

Comment 22:
Liquidated damages vary with company purchasing policy.

13.0 FINAL ACCEPTANCE

Final acceptance of the work supplied under this specification shall be rendered when the following conditions have been met:

1. Delivery requirements as specified have been accomplished.

2. Drawings submittals and Instruction Book requirements as specified.

3. Sufficient tests and inspections have been made by the Buyer to determine that the work meets all the requirements of the specification, including analyses under Section 8.0, and field tests under Section 7.0, and any written agreements between the Buyer and the Seller.

14.0 PAYMENT

Ninety percent of the total price shall become due and payable 30 days after delivery. The remaining ten percent shall become due upon final acceptance of the total system as previously defined.

15.0 EXCEPTIONS

Exceptions to this specification shall be itemized and described in detail in writing. Cost differential between specified and excepted shall be stated if applicable.

16.0 CORRESPONDENCE

All questions that the bidder/supplier may have regarding the proposal and all drawings associated with the project as previously outlined shall be directed as follows:

A. Correspondence Procedure (except drawing transmittal letters) After Issuance of Purchase Order

1. All correspondence (except drawing transmittal letters) relative to this Order shall be distributed as shown in the purchase order and bear the indicated Purchase Order Number. Correspondence shall be addressed as shown in the purchase order.

17.0 ENGINEERING DOCUMENTS

1. The following preliminary data shall be supplied with the quotation:

   a. Outline drawings of the skid base mounted equipment, electric schematic diagrams, including details of AC power input, output to motor, power processing, filtering and interfaces with the system, the motor, plant communication and instrumentation, foundation details; cooling, heating and ventilation system; electric power requirements for auxiliary equipment and calculated losses for the drive and motor at 100%, 75%, 50% and 25% speed.

   b. Package size for shipment and installation.

   c. Typical waveforms for operating range of Input and Output voltages, currents and motor speeds including harmonic spectra related to percentage of fundamental.

   d. General maintenance requirements and schedule.

   e. Design specification and descriptive literature for all major components of the drive system and ancillary systems.

f. Speed-time curve for the motor accelerating the specified load with the starting current limited to 150 percent of rated current and ramping to full speed.

g. A recommended spare parts list to obtain the expected life of the equipment with current prices and delivery times.

h. The Seller shall return to the Buyer certified data sheets in Attachment A and Attachment D, incorporating the required information.

i. The following information for isolation transformers:

1. Weight.
2. Outline dimensions and mounting details.
3. No load watt loss.
4. Watt loss at rated load.
5. Impedance.
6. Sound pressure level (dBA at rated load).
7. kVA rating.
8. Primary voltage.
9. Secondary voltage.
10. Insulation BIL.
11. Surge protection provided.

j. The following information for filter capacitors:

1. KVAR rating.
2. Voltage rating.
3. BIL rating.
4. Dielectric voltage stress at 110 percent rated voltage.
5. Corona starting voltage at 25 C.
6. Internal hot-spot temperature at 110 percent rated voltage.
7. Insulation dielectric system.
8. Maximum and average watts losses at 25 C.

k. The Seller shall provide detailed information on the operation of the control. Information should be provided on how easily the control can be tailored to specific applications, and on the diagnostic capabilities of the control.

l. The Seller shall provide detailed information on the drive capability during various failure and maintenance conditions.

m. The Seller shall submit reports on analysis of Section 8.0.

n. The Seller shall submit guarantees as required in Section 9.0

2. Approval Drawings - Two copies each of outline, control schematics and wiring diagrams prior to fabrication of equipment.

3. Final Documentation

a. Final Drawings - The Seller shall furnish one full size black on white reproducible such as an autopositive or Xerox 1860 vellum, made from the original tracing unfolded and two good quality full size, blue line prints made from the reproducible folded to 8-1/2 x 11 inch size of each design drawing. Drawing shall be of sufficiently high quality drafting and reproduction to permit microfilming. Internal wiring diagrams shall be laid out such that terminal blocks for Purchasers external connections have sufficient room, a minimum of one and one half inch, for showing cables for external connections. In addition to the above specific design drawings, the Seller shall supply 20 complete sets of their standard drawings showing control schematics, transistor schematics, wiring, outline dimensions, mounting details and equipment weight.

b. Instruction Books and Spare Parts List - Seller shall furnish to Purchaser as soon as possible 20 copies of all Instruction Books, Spare Parts List and any special bulletins covering on site storage.

c. Test Reports - Seller shall furnish to Purchaser 20 copies each of all standard test reports as required by Referenced Documents.

Comment 23:
Drawing test reports, instruction book and spare parts list requirements vary greatly among utilities and this section should be revised as required.

18.0 REPLACEMENT PARTS, AVAILABILITY OF PROGRAMMING

Seller shall identify the electronic components, programmable chips and batteries that are time degradable. Approximate life span of these devices shall be disclosed in maintenance procedures.

Seller shall give 60 days prior written notice of intent not to accept further orders for replacement parts. Upon written request thereafter by Buyer, Seller shall deliver to Buyer detail drawings, specifications and other information necessary to have these parts manufactured elsewhere by others to allow the Buyer to keep the ASDs in operation.

19.0 TRAINING

1. The Seller shall provide operator and maintenance training and start-up services. The cost of additional training and start-up services shall also be quoted.

20.0 FORM OF TECHNICAL INFORMATION

1. The "Form of Technical Information," Attachment D, shall be completed and returned with the Sellers proposal.

21.0 CONFLICTS AND ALTERNATES

1. Conflicting information shall be brought to the attention of the Buyer. Improvements to lower cost or improve performance shall be offered as an alternate.

Specification No.

ATTACHMENT A

ADJUSTABLE SPEED INDUCTION MOTOR DRIVE SYSTEM DATA SHEET

NOTE: SELLER TO COMPLETE DATA AND NOTE EXCEPTIONS.

1. ADJUSTABLE SPEED DRIVE MANUFACTURER/MODEL NO.: ____________________

2. SERVICE CONDITIONS:

   (a) Location: ____________________

   (b) Elevation above sea level: ____________________

   (c) Ambient temperature range: __________ °F to __________ °F

   (d) Relative humidity: ____________________

   (e) Wind loading ____________________

   (f) Duty: ____________________

   (g) Load WK^2: ____________________

   (h) Dust, micrograms/meter^3: ____________________

   (i) Rain/wind: ____________________

   (j) Other: ____________________

3. RATINGS AND FEATURES OF ASD:

   (a) Horsepower/kVA: __________ (b) Rpm: __________

   (c) Torque: __________ (d) Service factor: __________

   (e) Speed range: __________ (f) Maximum kVA/kVAR input: __________

   (g) Full load input/output current: ____________________

   (h) Type of surge protection equipment furnished: ____________________

   ____

   (i) Space heaters:

	Rated	Operated
Volts	________	________
Watts	________	________

   (j) Type/quantity/rating of current transformers furnished: ____________________

   ____

(k) Type/quantity/rating of potential transformers furnished: ____________

____

(l) Type terminations furnished for power cable: ____________

____

(m) Total weight: (1) house and skid ____ lb
(2) transformers ____ lb each

(n) Painting and finishing: ____________

____

(o) Metering equipment provided: ____________

4. Are fuses used in the power circuits? If so, please identify which circuits.

____

____

5. Is the rectifier/inverter capable of full operation with one thyristor cell failure? Is this condition annunciated? Please give a brief description.

____

____

6. Provide brief description of diagnostic system furnished. ____________

____

____

7. Provide description of cooling system furnished. ____________

____

____

8. Describe what is being proposed to counteract salt-air corrosion of ASD components. ____________

____

____

9. Describe possible extent of resonance of output filter with motor.

____

____

10. Describe possible self-excitation of motor with output filter after ASD trip.

____

____

11. LOSSES AND EFFICIENCY

Complete the following air-cooled, water-cooled, 6- and 12-pulse offerings.

	Operating Hours	Gross MW	Motor Speed, %	Motor RPM	Motor HP	Input XFMR	ASD	Cooling System	Total	Efficiency %
	0	825	101	900	7424	___	___	___	___	___
	0	785	96	857	6408	___	___	___	___	___
	279	735	90	802	5246	___	___	___	___	___
S	274	658	80	718	3778	___	___	___	___	___
A	291	582	71	634	2617	___	___	___	___	___
M	872	505	62	551	1759	___	___	___	___	___
P	909	429	53	469	1136	___	___	___	___	___
L	946	353	43	386	697	___	___	___	___	___
E	348	278	35	308	407	___	___	___	___	___
	436	198	26	229	203	___	___	___	___	___
	1133	121	26	228	200	___	___	___	___	___
	1939	60	25	228	200	___	___	___	___	___

12. SEMICONDUCTOR APPLICATION DATA

	Rectifier	Inverter
(a) Power semiconductor rating		
(1) Amperes continuous	________	________
(2) Peak reverse voltage	________	________
(b) Power semiconductor applications, full bridge		
(1) Amperes at ASD rating	________	________
(2) Peak reverse voltage, 4.0 kV applied	________	________
(c) Power semiconductor application (N+1)		
(1) Ampere at ASD rating	________	________
(2) Peak reverse voltage, 4.0 kV applied	________	________
(d) Number of power semiconductors in series	________	________

13. HARMONICS

% Speed	Input THD Voltage	Input THD Current	Output THD Voltage	Output THD Current
100	____	____	____	____
75	____	____	____	____
50	____	____	____	____
25	____	____	____	____

Specification No.

ATTACHMENT B

INDUCTION MOTOR DATA SHEET
ITEM 1

1. SERVICE CONDITIONS:

(a) Location: ______________________

(b) Elevation above sea level: ______________________

(c) Ambient temperature range: ______________________

(d) Relative humidity: ______________________

(e) Area classification: ______________________

(f) Duty: ______________________

(g) Load WK^2: ______________________

2. RATINGS AND FEATURES:

(a) Type motor: ______________________

(b) Horsepower: __________ (c) Voltage: Nominal __________

(d) Phase: __________ (e) Frequency: __________

(f) Service factor: __________ S/N __________ Model __________

(g) Full load speed: ______________________

(h) Insulation class: ______________________

(i) Temperature rise (by RTD): ______________________

(j) Full load current: __________ Locked rotor current: __________

(k) Full load torque: __________ Running light current: __________

(l) Starting torque: ______________________

(m) Efficiency: 100% load
75% load
50% load

(n) Power factor: 100% load
75% load
50% load

(o) Enclosure type: ______________________

Specification No.

(p) Rotation (when viewed from end opposite coupling): ______ cw/ccw ______

(q) Bearing type: ______

(r) Type lubricating system furnished: ______

______

(s) Space heaters: Volts ______

Watts ______

Specification No.

ATTACHMENT C

SUPPLEMENTAL DATA
ADJUSTABLE SPEED INDUCTION MOTOR DRIVE SYSTEM

1. SERVICE CONDITIONS

A. Equipment required for outdoor service shall be subject to the environmental conditions in section 3.A.

B. Input Power

Voltage: ________ 3-phase, rated voltage ± 10%

Frequency: ______________

Short circuit capacity: Normal ______ MVA for ______ kV level
Worst case ______ MVA for ______ kV level

2. RATING

Item No.	Service Equipment	Rated Horsepower	Max RPM	Rated Voltage	Qty
1	Adjustable Speed Drive				

Specification No.

ATTACHMENT D

FORM OF TECHNICAL INFORMATION FOR
ADJUSTABLE SPEED INDUCTION MOTOR DRIVE SYSTEM
PART I - PRICE AND SHIPPING INFORMATION

Seller ______________________

1. PRICE

	FOB Destination Freight Allowed
A. Total cost, FOB jobsite	
(1) Water-cooled 12-pulse rectifier with 6-pulse inverter	________
(2) Air-cooled 12-pulse rectifier with 6-pulse inverter	________
(3) Water-cooled 12-pulse rectifier with 12-pulse inverter	________
(4) Air-cooled 12-pulse rectifier with 12-pulse inverter	________
(5) Option for redundant microprocessor controls with bumpless transfer	________
(6) Harmonic analysis	________
(7) Torsional analysis	________
(8) Factory training course	________
(9) One-week on-site training course	________
B. Freight charges included in the price	________
C. Unit cost for recommended spare parts	________

2. ALTERNATIVE PRICE

Total Cost (the Bidder may quote changes in price for other suggested alternative. Identify deviations in detail). ________

3. TERMS OF PAYMENT

Page of the proposal where the terms of payment are defined ________

Specification No.

4. ESCALATION

A. Maximum escalation ______________

B. Page of the proposal where the method of determining escalation is described ______________

5. COST OF SERVICES OF FIELD ERECTION ENGINEER (SERVICE REPRESENTATIVE)

A. Services for (*) days, including food, lodging, transportation to and from temporary domicile to jobsite, and other expenses. The normal work week will be (*) hours or (*) days per week.

(1) Lump sum ______________

(2) Per diem for each additional day ______________

(3) Transportation ______________

6. SHIPMENT

A. Shipping point ______________

B. Shipping weight, lb ______________________________

____

C. Shipping method ______________

7. EXCEPTIONS TO SPECIFICATION

A. Does the proposal comply with the specifications? ______________

____

B. If the Bidder takes exception to the specification, indicate the page of the proposal where the exceptions are described. ______________

____

8. PROPOSED SCHEDULE

Receipt of purchase order ______________

Outline drawings, preliminary interconnection drawings ______________

Return of drawings ______________

Torsional analysis complete ______________

Elementary, wiring diagram and revised outline drawings ______________

Specification No.

8. PROPOSED SCHEDULE (CONT)

Engineering complete ____________

Factory test ____________

Shipment ____________

____
Company

____
Signature

____
Title

____
Reference Number

____
Date of Bid

Specification No.

FORM OF PROPOSAL

PART II - ENGINEERING INFORMATION

Bidder ______________________

1. SUBMITTALS

   A. Dimensional drawing numbers

      (1) Preliminary outline drawing number ______________
      ____
      ____
      ____

      (2) Preliminary circuit diagram number ______________
      ____
      ____
      ____

   B. Time in weeks after award of purchase order to furnish preliminary outline drawings ______________

   C. Completed Adjustable Speed Induction Motor Drive Data Sheets ______________

2. SHIPPING AND STORAGE

   A. Shipping weight, lb
      ( ) control house ______________
      ( ) skid ______________
      ( ) ______________
      ____

   B. Operating weight, lb
      control house ______________
      including skid ______________
      transformers ______________

   C. Maximum dimensions, length x width x height ______________
      ____
      ____
      ____

3. STATEMENT OF WARRANTY

____

ATTACHMENT E

DESCRIPTION OF BUS TRANSFER SCHEDULE
(SAMPLE)

Under normal operating conditions, the generating unit auxiliary power system is supplied from the generator terminals through the double secondary winding of the unit auxiliary transformer at voltages of 13,800 and 4,160 volts. The 13,800 volt bus supplies the power for both forced draft fans (FDFs) and both boiler feed booster pumps (BFBPs). The reserve 13,800- and 4,160-volt buses are supplied from the double secondary windings of a reserve auxiliary transformer whose primary is connected to a separate 66 kV source. Normally, open reserve bus tie breakers connect 13,800- and 4,160-volt reserve buses to the unit 1 and 2 buses.

Failure of the unit 13,800-volt bus would drop both FDFs and BFBPs. The failure of FDFs trips the boiler, while failure of both BFBPs runs the unit load back to 50 percent. On any unit shutdown or unit trip, the auxiliary power to the unit 13,800- and 4,160-volt buses will be restored from the reserve 13,800- and 4,160-volt buses immediately, either for orderly shutdown of the unit or to facilitate a hot restart as required. This fast bus transfer is accomplished by auto-closing of the reserve bus tie breakers in 5-8 cycles under supervision of a synchrocheck relay. If the fast bus transfer is blocked by excessive phase angle difference, the residual bus under-voltage relay will initiate a back-up bus transfer scheme when the unit bus voltage decays down from 50 to 30 percent (1/2 to 1 second or more).

If the backup transfer scheme fails to operate, the manual transfer between reserve and unit dead bus will be initiated by the operator.

ATTACHMENT F

COMPUTER CONTROL INTERFACE DESCRIPTION
(SAMPLE)

The ASD microprocessor-based control will receive an analog signal, 4-20 ma, for air flow demand which correlates to fan speed and, in turn, to motor speed. the control signal can be either hard-wired or properly accessed through the WDPF control system recently installed at Ormond Beach.

Other noncontrol signals are required to provide the control room operator with the necessary information relative to ASD performance, status, alarms and other related signals. These signals must properly access the WDPF control system.

It is suggested that all control and/or miscellaneous control signals be provided to the WDPF system via I/O modules which are compatible with an existing nearby control drop. The Seller should determine if this method is possible. Otherwise, the Seller should recommend an alternate to achieve this interface. The Seller shall also provide the Buyer with all the documentation required to operate, maintain or change any of his developed interface hardware and software.

Appendix E

FAN NOISE REDUCTION WITH ADJUSTABLE SPEED DRIVES

Appendix E

FAN NOISE REDUCTION WITH ADJUSTABLE SPEED DRIVES

INTRODUCTION

For fossil power plants, the sources of noise perceived by the surrounding communities primarily come from the draft fans. It is therefore appropriate to examine whatever effect adjustable speed drives may have on the sound emitted by such devices.

CHARACTERISTICS OF FAN NOISE

Typically, the sound produced by a fan consists of a tonal (or pitched) component superimposed on a broad-band (or unpitched) noise component. Figure E-1 exhibits the spectrum of a typical centrifugal fan in which the tonal components are clearly identifiable. The pitch of the tonal component or the fan tone is determined by the rotative speed of the fan shaft multiplied by the number of fan blades (i.e., the blade passing frequency). The dashed curve is for inlet vanes partially closed. This condition increases the sound at the blade passing frequency. The fan tone attests to periodic fluctuations of the pressure field created by the rotating fan blades. The broad-band noise reflects the random shedding and diffusion of vortices in the flow field. According to our experience, the tonal content of the fan noise is usually far more obtrusive in a community, since the broad-band content tends to blend in better with other sources of noise that are typically present in a community.

The noise from a fan is not constant but is affected by the manner in which it is operated. Figure E-2 displays the curves commonly used to describe the operating characteristics (namely total head, horsepower, and efficiency vs flow rate) of a centrifugal fan at essentially constant speed. These curves result from regulating the flow through the fan with a throttling device. In the upper portion of this figure appears the less familiar curve which shows how the total sound power output of the fan is affected by this method of flow regulation.

The plot shows that the fan is the quietest when operated at the point of peak efficiency. The emitted noise is substantially higher when it is operated at a

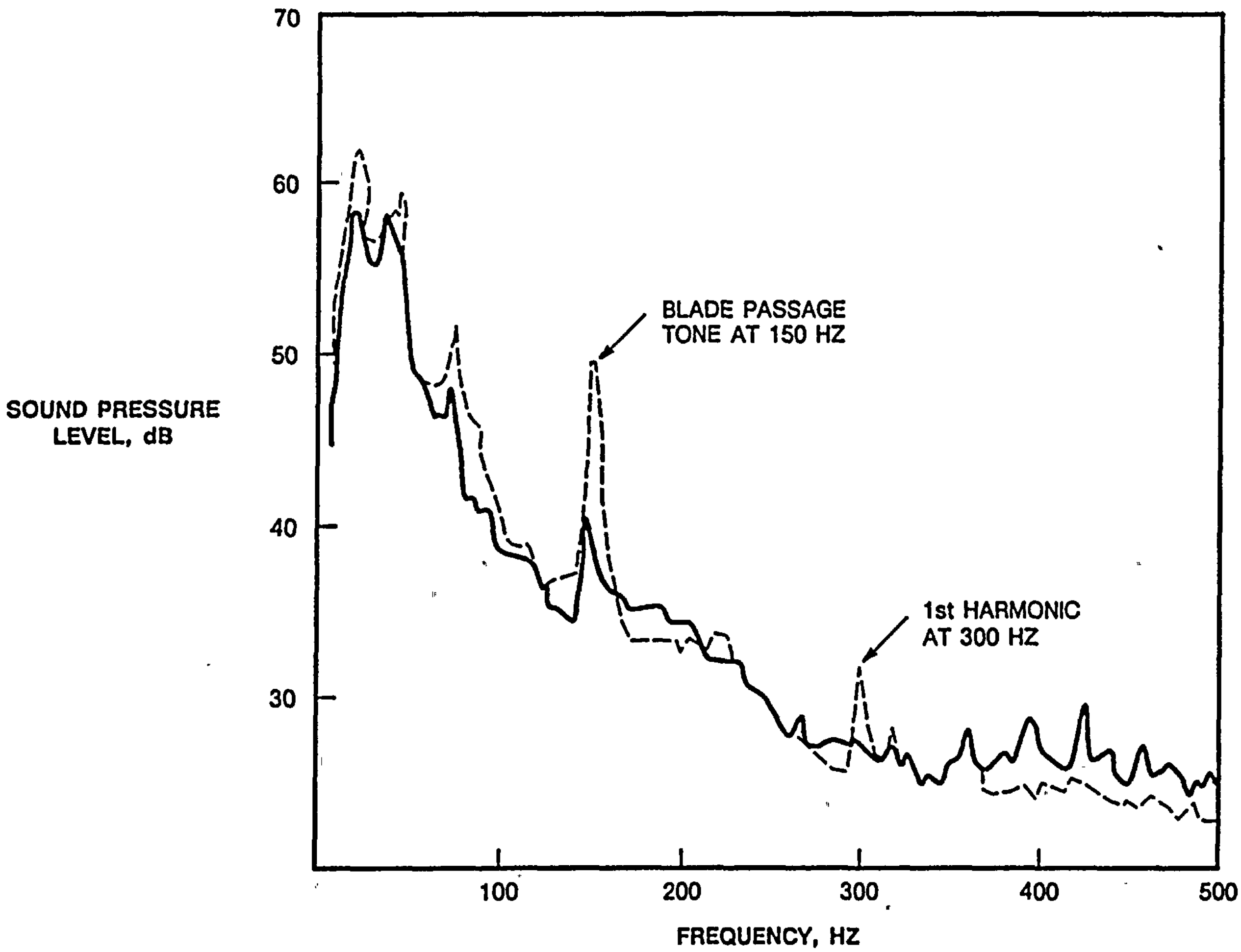

Figure E-1
CHARACTERISTICS OF SOUND PRODUCED BY A FAN

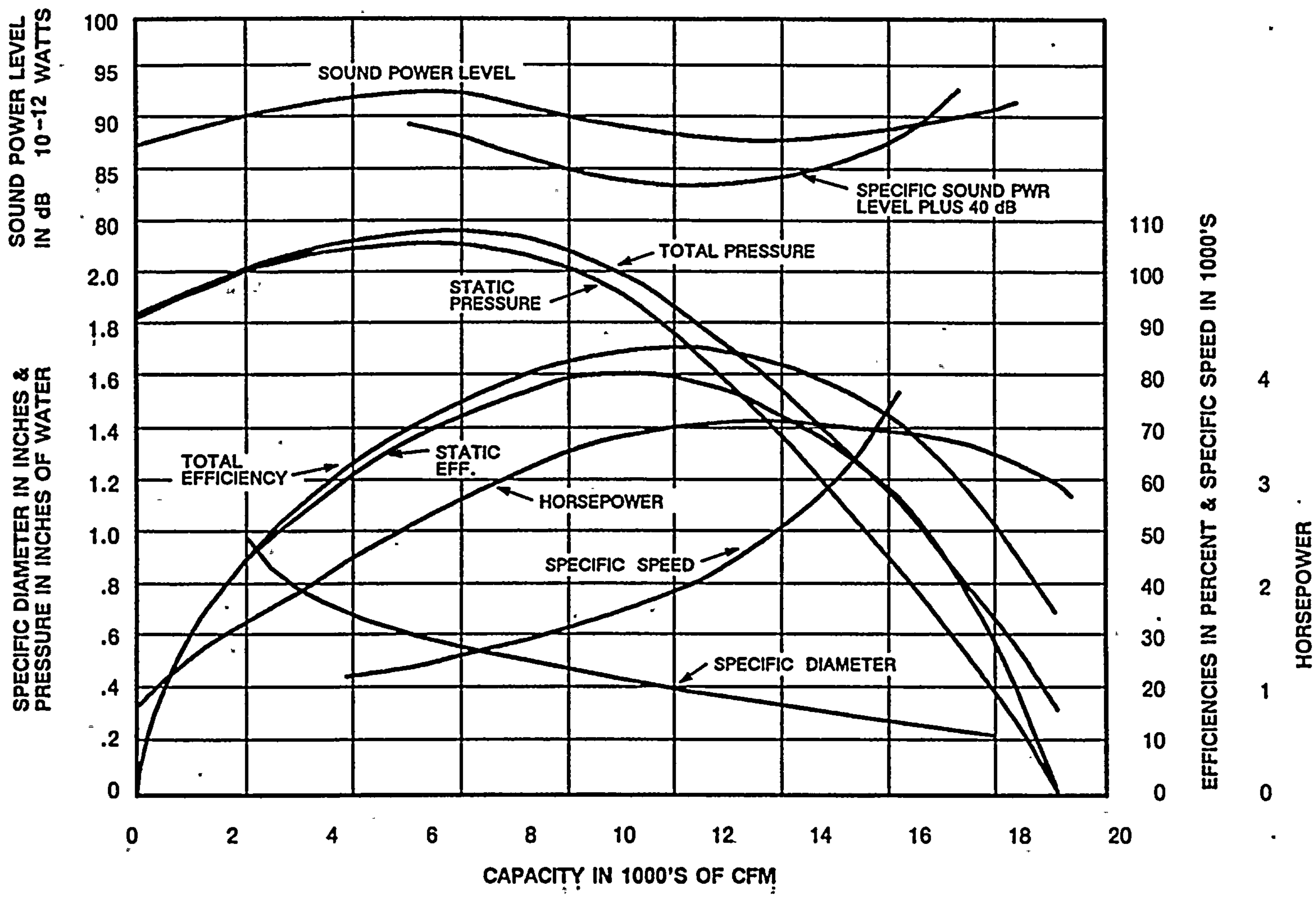

Figure E-2

TYPICAL CONSTANT SPEED PERFORMANCE CURVES FOR VENTILATING FANS
(FROM REFERENCE 1)

flow rate that is much less than that at peak efficiency. A similar behavior in terms of noise emission is exhibited by axial-flow fans, as shown in Figure E-3.

EFFECT OF CHANGING ROTATIONAL SPEED

The behavior of the fan is quite different if flow control is accomplished by varying its rotational speed while maintaining the system configuration constant. In this case, the performance of the fan, including its acoustics, follows simple scaling laws. For example, Figure E-4 depicts the pressure head and horsepower curves at three different speeds. The total sound power (expressed in decibels) emitted by the fan at one speed can be related to that at another speed by the formula shown in Figure E-5.

This formula illustrates the significant fact that the noise emitted by a fan can be expected to drop sharply with decreasing speed.

PERCEIVED NOISE FROM FANS

The perceived loudness of a fan would in reality go down faster than the rate predicted by the formula in Figure E-6. This is because of the fact that the sensitivity of human ear also drops with frequency from the peak sensitivity reached at about 2500 hz. The ANSI A-weighting function, which is based on empirical data, illustrates this fact. The use of the A-weighting function in rating community noise is a well established practice (Ref. 2).

The formula given in Figure E-7 has been used by the U.S. Environmental Protection Agency for evaluating the impact of noise on communities. In this formula, the daytime (7 am to 10 pm) level L_d is averaged with the nighttime (10 pm to 7 am) level to obtain a single composite number, L_{dn}. Notice that in this formula 10 decibels are added to the actual nighttime level L_n to account for the greater sensitivity to noise during that time span.

EXAMPLE

Figure E-8 illustrates the benefit that could result through the use of an ASD. In Case 1, we consider a fan that has a blade passing frequency of 150 hz and that produces a noise level of 60 decibels (A-weighted) at the plant boundary. For constant speed operation, the value of the L_{dn} would amount to 66 decibels. This assumes that the fan was not throttled back during periods of low power demand. If that were done the L_{dn} value would have been higher.

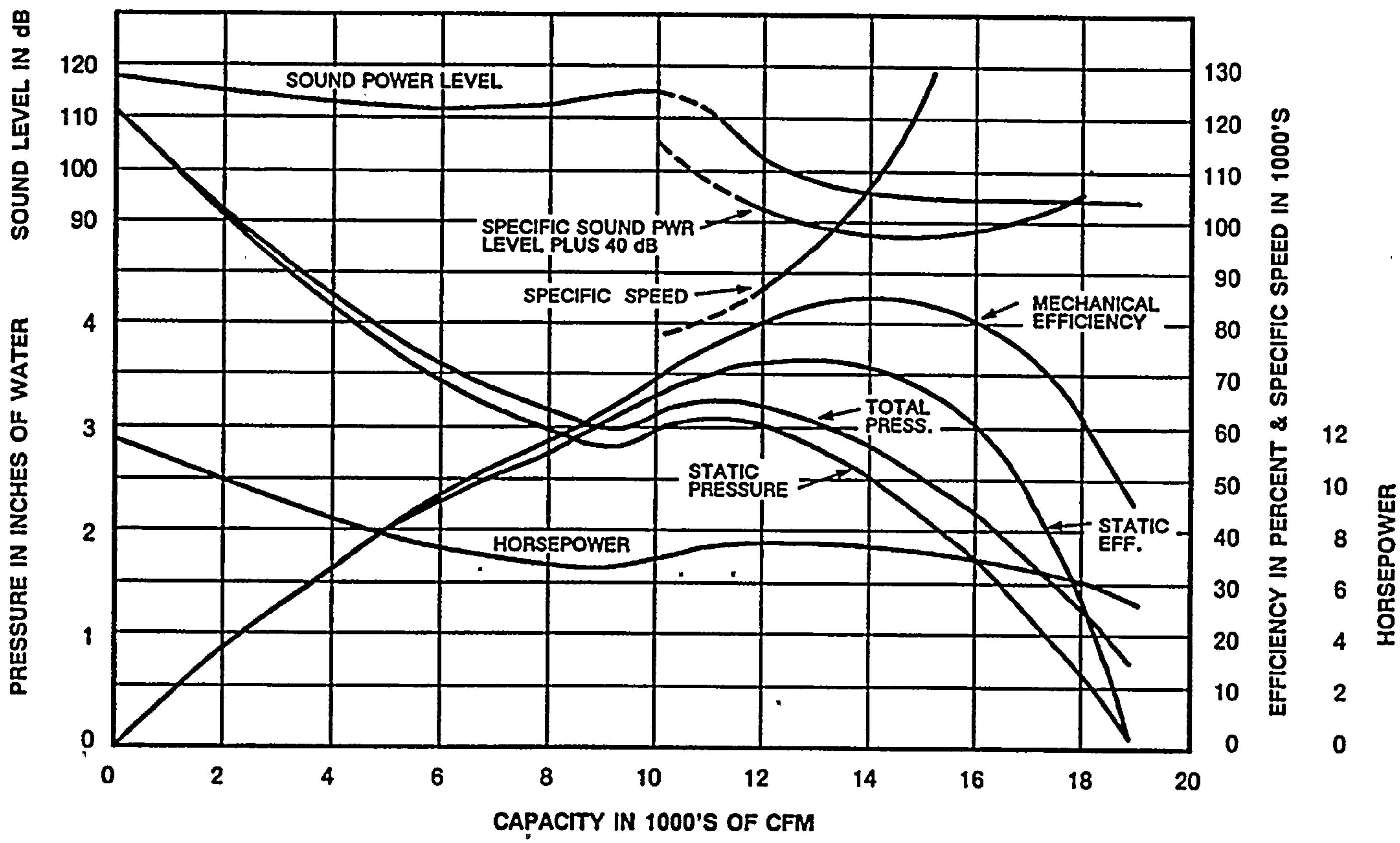

Figure E-3

TYPICAL CONSTANT SPEED PERFORMANCE CURVES FOR VANEAXIAL FANS
(FROM REFERENCE 1)

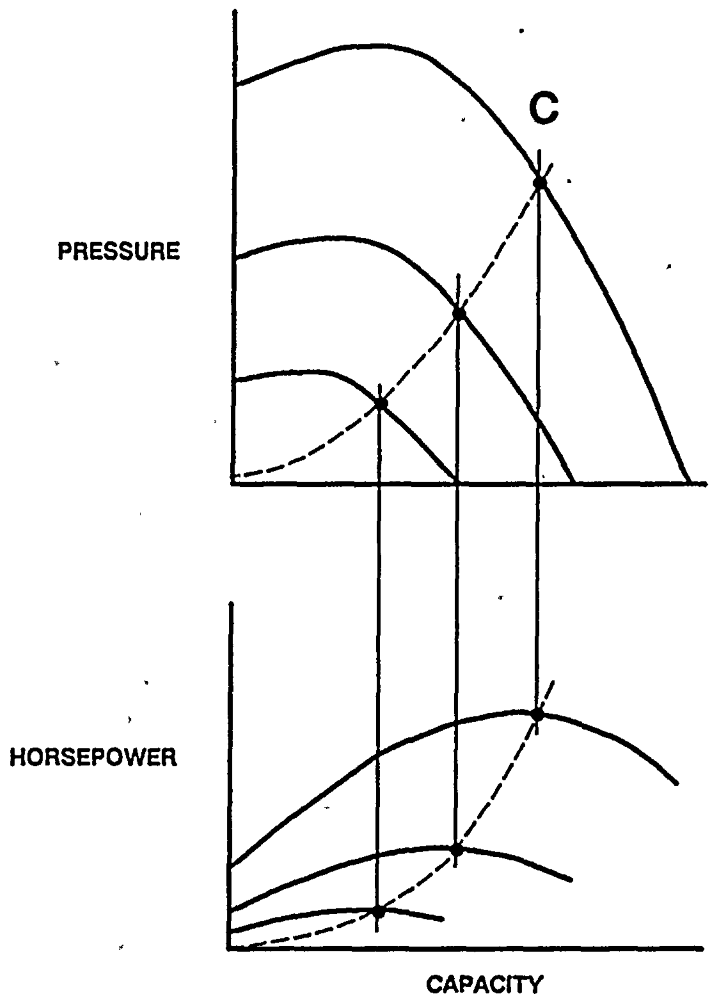

Figure E-4
FAN PERFORMANCE AT DIFFERENT SPEEDS
(FROM REFERENCE 1)

$$PWL_a = PWL_b + 70 \log_{10} \left(\frac{SIZE_a}{SIZE_b}\right) + 50 \log_{10} \left(\frac{RPM_a}{RPM_b}\right)$$

Figure E-5

VARIATION OF SOUND POWER OF FANS WITH SPEED
(AFTER REFERENCE 1)

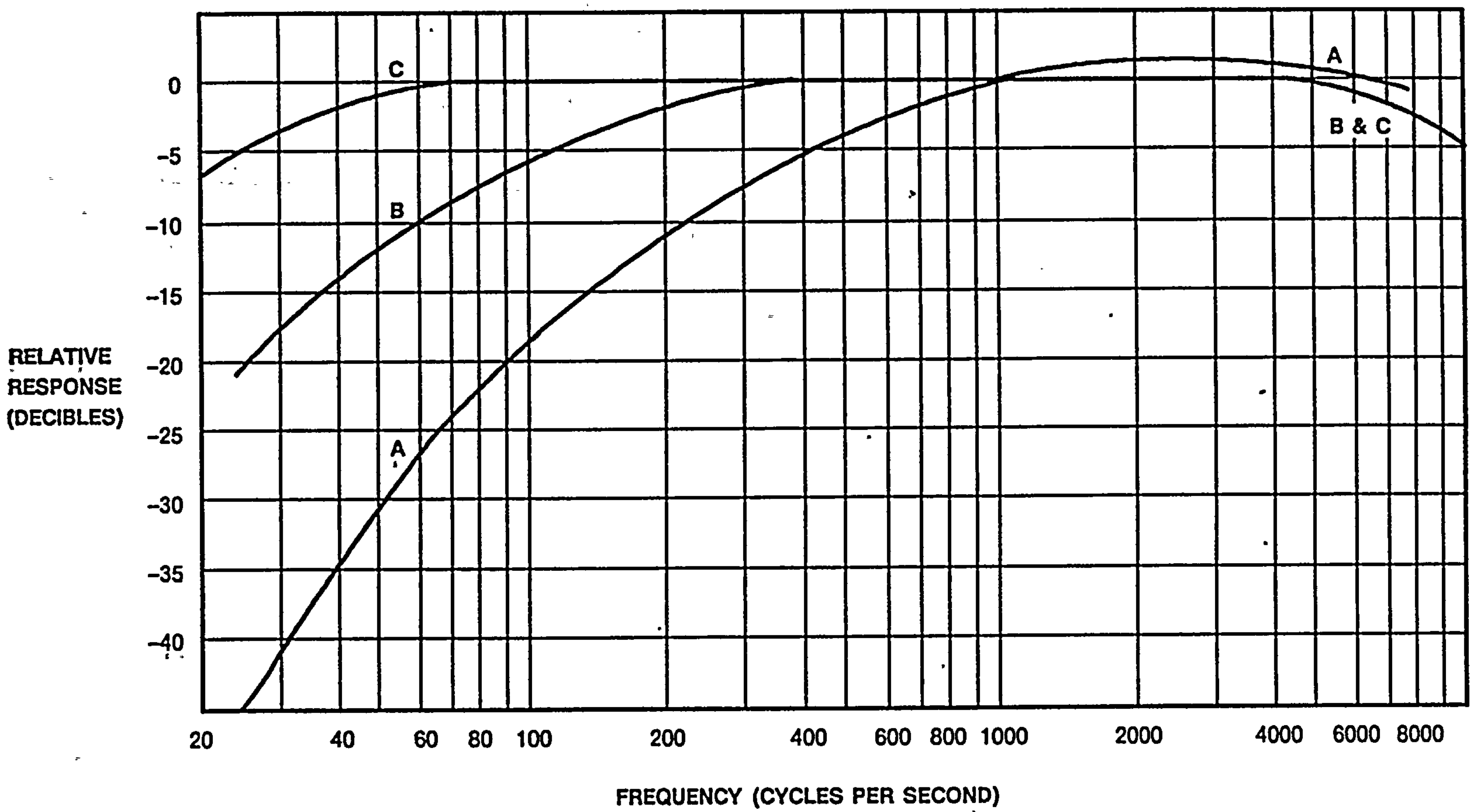

Figure E-6

A-WEIGHTING FUNCTION ACCORDING TO ANSI

$$L_{dn} = 10 \log \frac{1}{24} \left[15 \times 10^{(L_d/10)} + 9 \times 10^{(L_n + 10)/10} \right]$$

Figure E-7

FORMULA FOR CALCULATING COMPOSITE NOISE LEVEL

EXAMPLE

CASE 1:

L_d = 60 dB

L_n = 60 dB

L_{dn} = 66 dB

CASE 2:

L_d = 60 dB

L_n = 60 – 6 – 3 = dB

L_{dn} = 60 dB

Figure E-8
A SAMPLE CALCULATION

In Case 2, it is assumed that the fan operates at 3/4 speed during the nighttime hours. The L_n value then, in theory, would be reduced by 9 decibels with six decibels coming from the reduced sound power output and 3 decibels coming from reduced sensitivity according to the A-weighting function. The new L_{dn} value is thus only 60 decibels which is 6 decibels lower than in Case 1.

Figure E-9 can be used to help assess the effect of this reduction in noise on the surrounding community. This plot is derived from the case studies of reaction of communities to noise. The abscissa represents the noise level with each interval representing 5 decibels. No numerical values are attached to the noise levels as these values would depend on the socio-economic factors of the community. Let's assume that Case 1 leads to a rating of E which implies "wide-spread complaints". Then a 6 dB reduction may very well be sufficient to placate a majority of the residents.

Presented at ASD Forum
San Diego, December 1986
T. Y. Yen, Bechtel

REFERENCES

1. R. Jorsensen, Fan Engineering, Buffalo Forge Co., New York, NY, 1970.

2. Bolt Beranck and Newman, Inc., Electric Power Plant Environmental Noise Guide, Edison Electric Institute, New York, NY, 1978.

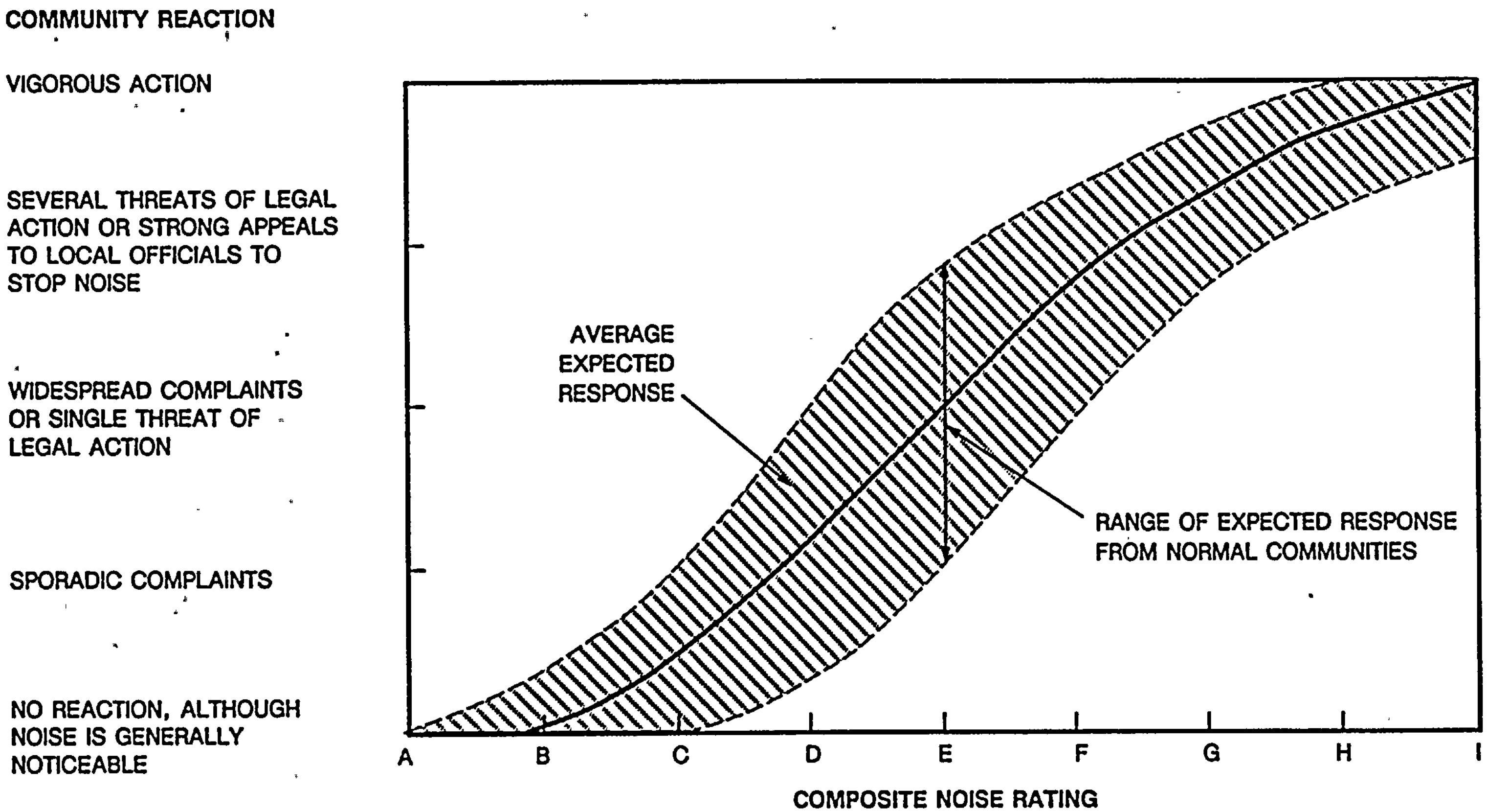

Figure E-9

CORRELATION OF COMMUNITY REACTION WITH COMPOSITE NOISE RATING
(FROM REF. 2)

ATTACHMENT 3

Discussion of the ASD output filter capacitor failure modes, failure probabilities, and the associated effects.

ASD OUTPUT FILTER CAPACITORS

The filter capacitors connected to the ASD output circuit are designed to reduce the ASD harmonics that are transmitted to the RRC pump motor. Nine oil filled capacitors are connected in parallel for each of the three phases of each channel, resulting in 27 filter capacitors per channel. Since each ASD has two channels, there are a total of 54 filter capacitors per ASD. The filter capacitor assemblies are identified as "Filter" in Figure 2A of the Reference 3 submittal.

Capacitors are very reliable components. The attached excerpt from EPRI report TR-101140, "Adjustable Speed Drives," calculates the mean time between failure (MTBF) for capacitor circuits to be 625,000 hours. GE supplied the capacitors for the ASDs installed at WNP-2 and, in the attached excerpt, they report an average failure rate of 0.03% per year. Given that one capacitor would cause a circuit failure, the EPRI MTBF translates to one capacitor circuit failure every 71 years. The GE average failure rate, given 54 capacitors, translates to one capacitor circuit failure every 61 years.

Capacitors usually fail such that a short circuit occurs between the input and output terminals. For example, shorting a capacitor due to a loss of dielectric will ground that phase and cause a protective ASD trip and actuate the associated control room alarm. Capacitors rarely fail such that an open circuit occurs. An open circuit condition can only be caused by failure of the capacitor leads due to an installation error or by vibration during operation. Any capacitor installation errors would have been discovered and corrected during the ASD functional testing conducted in June 1995. No capacitor installation errors were found during the testing. Capacitor lead failures due to vibration are unlikely since the ASD itself does not cause significant vibration and the ASD is not attached to a structure that is subject to significant vibration.

Failing a capacitor such that an open circuit is created will reduce the capacitance of the circuit. The reduction in capacitance changes the RRC pump motor inductance (L) - capacitance (C) filter circuit resonant frequency and increases the harmonics that are transmitted to the motor. Increasing the motor harmonics will lead to additional harmonics related heating of the RRC pump motor and may increase the motor air-gap torque pulsations. RRC pump motor winding temperatures are monitored, recorded, and alarmed in the control room. Thus, control room indication is available to detect abnormal motor heating caused by an ASD capacitor circuit failure. Motor vibration equipment would indicate if harmful vibration is being produced by motor air-gap torque pulsations. A discussion of the vibration monitoring equipment and associated control room alarms is contained in Appendix B, pages 6 and 7, of the Reference 3 submittal.

Adjustable Speed Drives

APPLICATIONS GUIDE

TR-101140
Research Projects: 2951-11, 2951-12, and 2951-04
Final Report, December 1992

Prepared by

JAMES A. OLIVER

Principal Investigator

JARSCO Engineering Corp.
Corona, CA 91719

In cooperation with

JAMES N. POOLE
CRS Sirrine Engineers, Inc.
Raleigh, NC 27606

and

TEJINDAR P. SINGH, P.E.
Danville, CA 94506

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304

EPRI Project Manager

MAREK J. SAMOTYJ
Power Electronics & Controls Program
Customer Systems Division

The two competing ASD technologies that were available on the market were studied in the field tests. They are the current-source, GTO-PWM inverter and the modified LCI. Another GTO-based technology has been introduced since the field tests were conducted. This is the voltage-source, star-modulated, PWM ASD.

The question is often asked about mean time between failures (MTBF) for ASDs and ASD components. A recently published[12-2] report by one manufacturer has proposed that the MTBF hours for components and for ASDs are as shown in Table 12-1. This approach to defining ASD reliability is challenged by another manufacturer, indicating that an analysis of ASD operating experience shows that the MTBF for medium-voltage ASDs may be as long as 40 years.

Table 12-1
MTBF hours calculated from ASDs and components

Component	MTBF Hours
Thyristor	33×10^6
GTO	1.7×10^6
Digital Control	100,000 to 200,000
Water Cooling System	1.0×10^6
Capacitor Circuits	625,000
Circuit Breakers	1.4×10^6
Input Transformer	1.8×10^6
Air Core Reactor	100×10^6
CTs and PTs	2.5×10^6
ASD	46,000
ASD With (N + 1)	48,000
ASD With Redundant Controls	103,000
ASD With Dual Channel	120,000
ASD With Common Spare	137,000

GE CAPACITOR & POWER PROTECTION
ALL FILM CAPACITOR FAILURE RATE INFORMATION

FIELD EXPERIENCE - ALL FILM HIGH VOLTAGE CAPACITORS

		FAILURE RATES			# OF FAILURES REPORTED	
YEAR OF MANUFACTURE	# OF UNITS PRODUCED	YEAR OF MFG	YEAR FOLLOWING	INDICATED ANNUAL RATE	YEAR OF MFG	YEAR FOLLOWING
1979	6084	0.00%	0.02%	0.02%	0	1
1980	21901	0.02%	0.05%	0.07%	4	11
1981	47030	0.01%	0.03%	0.04%	5	14
1982	44363	0.02%	0.03%	0.05%	9	13
1983	79977	0.01%	0.02%	0.03%	8	16
1984	84961	0.01%	0.01%	0.02%	8	8
1985	92716	0.01%	0.03%	0.04%	9	28
1986	77393	0.01%	0.02%	0.03%	8	15
1987	58462	0.00%	0.01%	0.01%	0	6
1988	68329	0.01%	0.02%	0.03%	6	12
1989	72343	0.02%	0.02%	0.04%	12	15
1990	70708	0.01%	0.03%	0.04%	7	18
1991	53466	0.00%	0.02%	0.02%	0	10
1992	80522	0.00%	0.01%	0.01%	1	8
1993	60287	0.01%		0.01%	6	
TOTAL	918542	0.01%	0.02%	0.03%	83	175

X:\FAILRATE\FAILRATE.XLS
04-Feb-94

To: Bob Ross
8 425 4447 fax

From: George Newcomb
8 234 5705 phone

ATTACHMENT 4

Discussion of the Supply System's evaluation of harmonics related heating of the nonsafety-related motor loads downstream of the SH-5 and SH-6 buses (includes an excerpt from NEMA MG-1-1987).

MOTOR DERATING

NEMA Standard MG-1-1987, Part 17A (see attached), addresses motor application considerations for constant speed motors used on a sinusoidal bus with harmonic content. This application standard applies to NEMA Designs A and B squirrel-cage induction motors rated 600 V or less with horsepower ratings less than 500 horsepower. The standard assigns a derating factor for induction motors based on the calculated Harmonic Voltage Factor (HVF) and the use of Figure 17A-1 (attached) in the standard. The HVF is defined as follows:

$$HVF = \sqrt{\sum\left(\frac{V_n^2}{n}\right)}$$

Where: n = order of odd harmonic, not including those divisible by 3, and
V_n = the per unit magnitude of the voltage at the nth harmonic frequency.

To reduce the possibility of damage to motors, the standard states that the rated horsepower of the motor should be multiplied by the factor shown in Figure 17A-1.

A HVF of 0.02779 was calculated for the 6.9 KV SH-5 and SH-6 buses for 100 percent drive speed in the startup mode of operation. The derating factor from Figure 17A-1 corresponding to this HVF is 1.0, which indicates that the rated horsepower of the motor loads is the nameplate rating (no derating required). The HVF calculated for the SH-5 and SH-6 buses is considered worst case since these buses are closest to the ASD harmonics source. The HVF for the nonsafety-related motor loads downstream of the SH-5 and SH-6 buses (e.g., 480 V cooling tower fan motors) would be lower due to the increased separation from the harmonics source. As previously discussed, the harmonics on the safety-related buses in the startup and generation modes of operation are very low. Thus, the HVF is negligible for the safety-related motors and no derating is necessary.

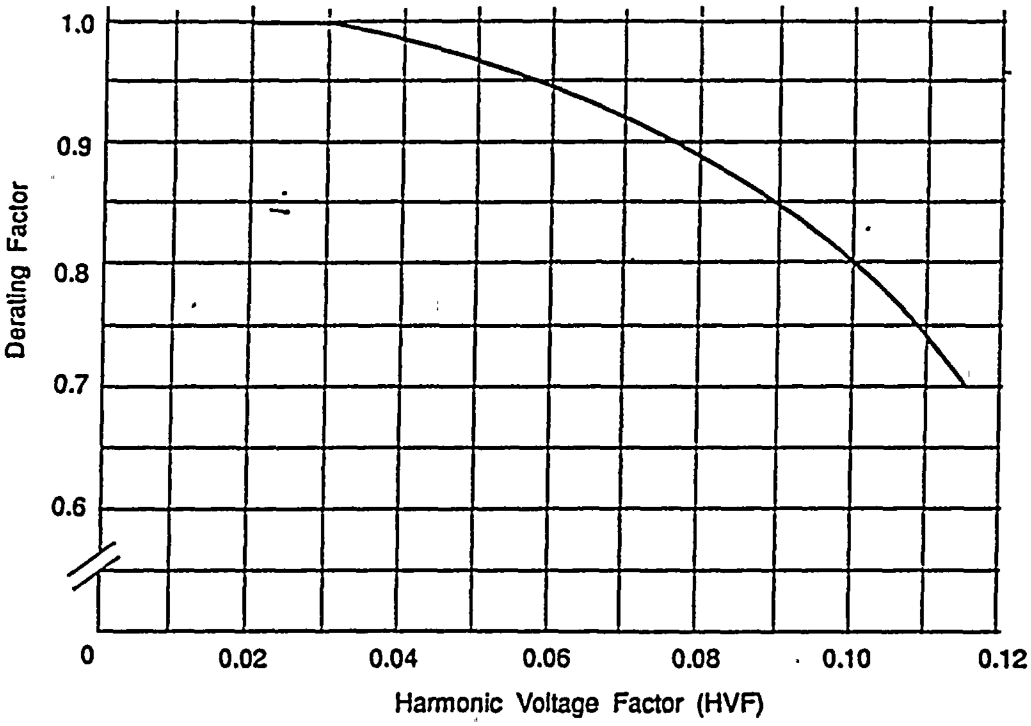

Figure 17A-1
PROPOSED DERATING CURVE FOR HARMONIC VOLTAGES

that such bus-connected capacitor banks be sized so that proper bus voltage limits are maintained. (See MG1-14.43.)

Authorized Engineering Information 11-16-1989.

MG1-17A.04 APPLICATION CONSIDERATIONS FOR MOTORS USED WITH VARIABLE-VOLTAGE AND VARIABLE-FREQUENCY CONTROLS

17A.04.1 Torque

17A.04.1.1 OPERATION BELOW BASE SPEED

The torque produced by an ac motor is approximately proportional to the ratio of the input (fundamental) voltage divided by frequency. Therefore, to develop constant torque below base speed the input voltage should be varied to maintain approximately rated volts per Hertz. At frequencies below approximately 30 Hz an increase in the volts per Hertz ratio may be required to maintain constant torque. For applications that require less than rated torque below base speed, system economics may be improved by operation at a reduced volts per Hertz ratio.

17A.04.1.2 OPERATION ABOVE BASE SPEED

Above base speed, an input voltage having a fundamental component equal to rated motor voltage should be maintained for constant horsepower operation. The maximum (breakdown) torque capability of the motor will limit the maximum speed at which constant horsepower operation is possible (refer to the motor manufacturer).

17A,04.2 Current

17A.04.2.1 RUNNING CURRENT

Inverters are generally rated in terms of a continuous current carrying capacity, a short term current carrying capacity, and a peak current capacity. To properly choose the size of inverter required in an application, consideration should be given to the peak and transient values in addition to the rms value of motor current, and the manner in which the system is to be operated. Because some level of current will exist at each of the harmonic frequencies characteristic of the particular type of inverter, the total root mean square (rms) sum of current required at full load may be from 5 percent to 10 percent greater than that level of current corresponding to operation on a sinusoidal power source. The magnitude of the peak values of the current waveform may vary from 1.3 to 2.5 times the rms value of the current, depending on the type of inverter considered and the motor characteristics. An additional margin from 10 percent to 50 percent in the current rating of the inverter should be considered to allow for possible overload conditions on the motor so as not to trip the inverter on such short time overcurrent demand. When the motor and inverter are used in a system where sudden changes in load torque or

Part 17A
APPLICATION CONSIDERATIONS FOR CONSTANT SPEED MOTORS USED ON A SINUSOIDAL BUS WITH HARMONIC CONTENT AND GENERAL PURPOSE MOTORS USED WITH VARIABLE-VOLTAGE OR VARIABLE-FREQUENCY CONTROLS OR BOTH

MG1-17A.01 SCOPE

The information in this section applies to NEMA Designs A and B squirrel-cage motors rated 600 volts or less, 500 horsepower or less when used on a sinusoidal bus with harmonic content; or when used with variable-voltage or variable-frequency controls or both.

NEMA Designs C and D motors are excluded from this section and the manufacturer should be consulted regarding their application.

For motors intended for use in hazardous (classified) locations refer to 17.04.10.

Authorized Engineering Information 11-16-1989.

MG1-17A.02 DEFINITIONS

17A.02.1 Motor Base Rating

When a motor is applied to an inverter, the base rating shall be the nameplated horsepower, voltage, frequency, speed, and torque (as determined from horsepower and speed).

17A.02.2 Motor Output Capability

The motor is capable of producing constant torque (horsepower proportional to speed) at and below base speed, and constant horsepower (torque inversely proportional to speed) at and above base speed, except where limited by the following:

a. Effect of reduced speed on cooling. (See 17A.04.5.)
b. Additional losses introduced by harmonic content. (Under consideration.)

NEMA Standard 11-16-1989.

MG1-17A.03 APPLICATION CONSIDERATIONS FOR CONSTANT SPEED MOTORS USED ON A SINUSOIDAL BUS WITH HARMONIC CONTENT

17A.03.1 Efficiency

Efficiency will be reduced when a motor is operated on a bus with harmonic content. The harmonics present will increase the electrical losses which decrease efficiency. This increase in losses will also result in an increase in motor temperature, which further reduces efficiency.

17A.03.2 Derating for Harmonic Content

Harmonic currents are introduced when the line voltages applied to a polyphase induction motor include voltage components at frequencies other than nominal (fundamental) frequency of the supply. Consequently, the temperature rise of the motor operating at a particular load and per unit voltage harmonic factor will be greater than that for the motor operating under the same conditions with only voltage at the fundamental frequency applied.

When a motor is operated at its rated conditions and the voltage applied to the motor consists of components at frequencies other than the nominal frequency, the rated horsepower of the motor should be multiplied by the factor shown in Figure 17A-1 to reduce the possibility of damage to the motor. This curve is developed under the assumption that only harmonics equal to odd multiples (except those divisible by three) of the fundamental frequency are present. It is assumed that any voltage unbalance or any even harmonics or both present in the voltage are negligible. This derating curve is not intended to apply when the motor is operated at other than its rated frequency nor when operated from a variable voltage or a variable frequency power supply or both.

Harmonic Voltage Factor (HVF) Defined

The harmonic voltage factor (HVF) is defined as follows:

$$HVF = \sqrt{\sum_{n=5}^{n=\infty} \frac{(Vn)^2}{n}}$$

Where:

n = order of odd harmonic, not including those divisible by three

Vn = the per-unit magnitude of the voltage at the nth harmonic frequency

Example: With per-unit voltages of 0.10, 0.07, 0.045, and 0.036 occurring at the 5, 7, 11, and 13th harmonics, respectively, the value of the HVF is:

$$\sqrt{\frac{0.10^2}{5}+\frac{0.07^2}{7}+\frac{0.045^2}{11}+\frac{0.036^2}{13}} = 0.0546$$

17A.03.3 Power Factor Correction

The proper application of power capacitors to a bus with harmonic currents requires an analysis of the power system to avoid potential harmonic resonance of the power capacitors in combination with transformer and circuit inductance. For power distribution systems which have several motors connected to a bus, power capacitors connected to the bus rather than switched with individual motors are recommended to minimize the potential combinations of capacitance and inductance, and to simplify the application of any tuning filters that may be required. This requires

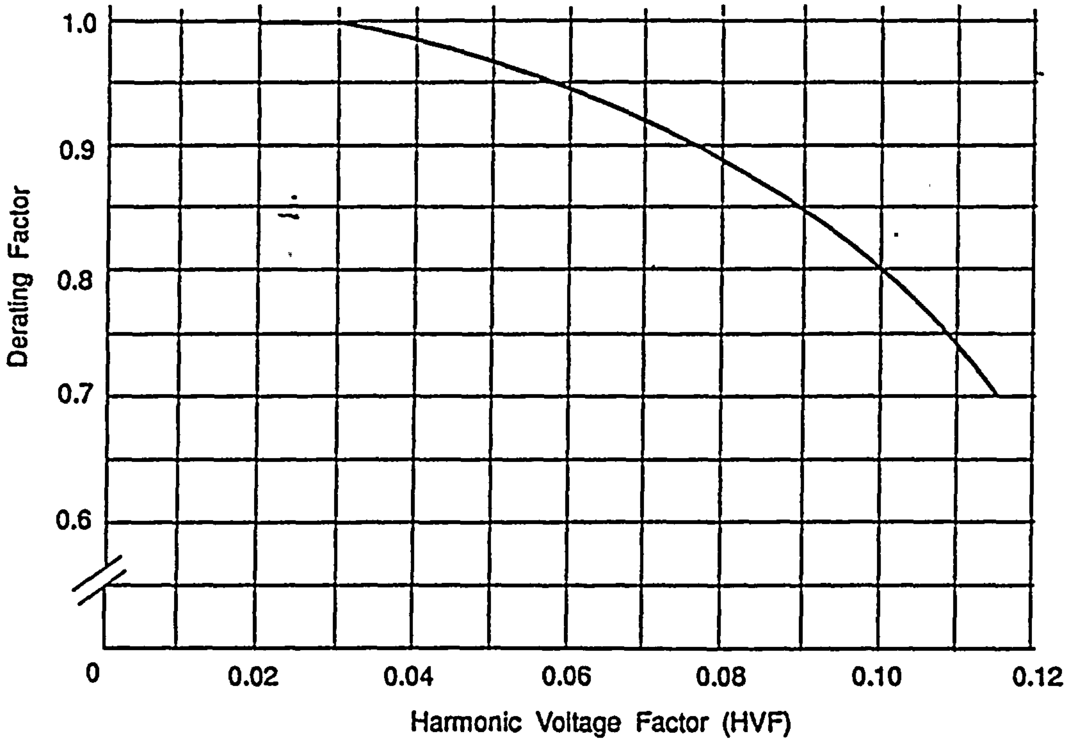

Figure 17A-1
PROPOSED DERATING CURVE FOR HARMONIC VOLTAGES

that such bus-connected capacitor banks be sized so that proper bus voltage limits are maintained. (See MG1-14.43.)

Authorized Engineering Information 11-16-1989.

MG1-17A.04 APPLICATION CONSIDERATIONS FOR MOTORS USED WITH VARIABLE-VOLTAGE AND VARIABLE-FREQUENCY CONTROLS

17A.04.1 Torque

17A.04.1.1 Operation Below Base Speed

The torque produced by an ac motor is approximately proportional to the ratio of the input (fundamental) voltage divided by frequency. Therefore, to develop constant torque below base speed the input voltage should be varied to maintain approximately rated volts per Hertz. At frequencies below approximately 30 Hz an increase in the volts per Hertz ratio may be required to maintain constant torque. For applications that require less than rated torque below base speed, system economics may be improved by operation at a reduced volts per Hertz ratio.

17A.04.1.2 Operation Above Base Speed

Above base speed, an input voltage having a fundamental component equal to rated motor voltage should be maintained for constant horsepower operation. The maximum (breakdown) torque capability of the motor will limit the maximum speed at which constant horsepower operation is possible (refer to the motor manufacturer).

17A.04.2 Current

17A.04.2.1 Running Current

Inverters are generally rated in terms of a continuous current carrying capacity, a short term current carrying capacity, and a peak current capacity. To properly choose the size of inverter required in an application, consideration should be given to the peak and transient values in addition to the rms value of motor current, and the manner in which the system is to be operated. Because some level of current will exist at each of the harmonic frequencies characteristic of the particular type of inverter, the total root mean square (rms) sum of current required at full load may be from 5 percent to 10 percent greater than that level of current corresponding to operation on a sinusoidal power source. The magnitude of the peak values of the current waveform may vary from 1.3 to 2.5 times the rms value of the current, depending on the type of inverter considered and the motor characteristics. An additional margin from 10 percent to 50 percent in the current rating of the inverter should be considered to allow for possible overload conditions on the motor so as not to trip the inverter on such short time overcurrent demand. When the motor and inverter are used in a system where sudden changes in load torque or