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Evaluation of Battery Converters Based on 4.8-MW Fuel Cell Demonstrator Inverter

Final Report

October 1980

**Prepared For:
U.S. Department of Energy
Assistant Secretary for Resource Applications
Power Supply Integration Division
Under Contract No. AC01-76ET26961**

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ABSTRACT

Electrical power conditioning is a critical element in the development of advanced electrochemical energy storage systems. This program evaluates the use of existing self-commutated converter technology (as developed by the Power Systems Division of United Technologies for the 4.8-MW Fuel Cell Demonstrator) with modification for use in battery energy storage systems.

The program consists of three parts:

- Evaluation of the cost and performance of a self-commutated converter modified to maintain production commonality between battery and fuel cell power conditioners
- Demonstration of the principal characteristics required for the battery application in MW-scale hardware
- Investigation of the technical requirements of operation isolated from the utility system.

A power-conditioning system consisting of a self-commutated converter augmented with a phase-controlled rectifier was selected and a preliminary design prepared. A principal factor in this selection was production commonality with the fuel cell inverter system. Additional types of augmentation, and the use of a self-commutated converter system without augmentation, were also considered. A survey of advanced battery manufacturers was used to establish the dc interface characteristics.

The principal characteristics of self-commutated converter operation required for battery application were demonstrated using an available 0.5-MW development system.

A survey of five REA and municipal utilities and three A&E firms was conducted to determine technical requirements for operation in a mode isolated from the utility. Definitive requirements for this application were not established because of the limited scope of this study.

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The effort reported herein was carried out by personnel at Power Systems Division of United Technologies. The work was performed by the Electrical Systems Group headed by Mr. G. A. Phillips. Mr. J. W. Walton directed the technical effort. Mr. J. M. King was the Program Manager. The following United personnel in addition to authors are gratefully acknowledged for their efforts in completing the various program tasks: Messrs. K. Lipman, M. M. Mendes, G. J. Messer, S. T. Kohn, and J. R. Vivirito. Mr. S. C. Caldwell of Electric Technology, Inc. served as consultant on the program.

In addition, we acknowledge the contributions of the battery manufacturers, utility companies, those A&E organizations that provided information on battery characteristics and updated operation requirements. Finally, we acknowledge the comments and suggestions made by Mr. J. C. Smith, the DOE Project Manager.

GLOSSARY

Augmented Converter - A converter using auxiliary equipment to increase its operating dc voltage range and/or power handling capability.

Converter - A device or system that changes alternating-current power to direct-current power and vice versa.

Inverter - A device or system that changes direct current power to alternating-current power.

Power Conditioner - The overall system required to convert power delivered by the energy source into the form required by the user. It includes the converter, switchgear, protection, step-up transformer, and any required filters or capacitors.

Rectifier - A device or system that converts alternating-current power into direct-current power.

Self-Commutated Inverter or Converter - An inverter or converter in which the energy required for commutation of the power semiconductors in the main switching position is provided by energy stored within the inverter or converter.

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Note: Appendices is available upon request. Inquires should be sent to:

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SECTION 1

EXECUTIVE SUMMARY

SECTION 1. EXECUTIVE SUMMARY

PROGRAM OBJECTIVES

Power conversion is a critical element in electrochemical energy storage systems. The objective of this program is evaluation of existing self-commutated converter technology in electrochemical energy storage systems, including the Battery Energy Storage Test (BEST) facility.

The inverter technology evaluated is that being developed by the Power Systems Division (PSD) of United Technologies Corporation for the FCG-1 fuel cell power plant. The inverter system is rated at 27.6-MW gross ac output and consists of three identical 9.2-MW modules. Only minor modification of the FCG-1 inverter bridges is permitted for the battery application in order to maintain commonality in production hardware. A derated version of one module has been fabricated for use with the 4.8-MW (dc) Fuel Cell Demonstrator under DOE/EPRI Contract EX-76-C-01-2102 (1). The unit will be tested at a Consolidated Edison site in lower Manhattan, New York (2). This inverter technology is referred to hereafter as the FCG-1 inverter.

The program objectives include selection of the most attractive modification of the fuel cell inverter system for battery converter application, a test of self-commutated converter features, and a preliminary specification for isolated operation.

The contractual goals for the self-commutated battery converter system are: a selling price of \$60/kW in 1975 dollars (based upon production of 50 27.6-MW systems in 1982); average full-power efficiency during either rectifier (battery charging) or inverter (battery discharging) operation greater than 95 percent; and average quarter-load efficiency, in either rectifier or inverter operation, greater than 90 percent.

The work is carried out in three tasks, as follows:

- Task 1 - Select Modification of FCG-1 Inverter
- Task 2 - Test Self-Commutated Converter Features
- Task 3 - Define Preliminary Specification for Isolated Operation

TASK 1 - SELECT MODIFICATION OF FCG-1 INVERTER

The 27.6-MW FCG-1 fuel cell Inverter system is designed for fuel cell operation in the inversion mode. This self-commutated approach has the ability to operate in both the inverter and rectifier modes with appropriate component ratings and controls. The work under this task selects the most attractive modification for battery converter operation and provides a preliminary estimate of the characteristics.

Selection of Modification

Selection of the most attractive modification was accomplished in the following manner:

- 1) The electrical interface requirements were defined based on a survey of six advanced battery manufacturers and information from United's fuel cell programs.
- 2) The analytical and design models of the inverter system were modified to include rectifier operation.
- 3) The performance of the FCG-1 inverter modified for converter operation with the advanced batteries was estimated. The degree of modification was such that this was found to be an unattractive approach.

- 4) Changes to the basic system configuration were evaluated and a system employing the use of a conventional phase-controlled rectifier to augment the converter derived from the FCG-1 inverter system was selected, and the performance and cost characteristics were estimated. The phase-controlled rectifier is employed during the rectifier mode only.

The survey of the six advanced battery manufacturers under Department of Energy direction led to the selection of two battery duty cycles for principal consideration. These are the 7-hour charge/10-hour discharge cycle and the 7-hour charge/5-hour discharge cycle. The dc voltage range, as expressed in terms of the dc voltage ratio end-of-charge voltage to end-of-discharge voltage, is one of the major design parameters affecting the cost and performance. Overall dc voltage ratios of 1.6 to 1 and 1.7 to 1 were selected for the 7-hour charge/10-hour discharge and the 7-hour charge/5-hour discharge cycles, respectively. This selection will handle all the battery cases except one type of lithium metal sulfide battery. A dc voltage ratio value of 1.3 to 1 was selected as the design value for the discharge portion of the battery cycle.

Modification of the design and analytical models included modification of the hybrid simulator models, which are used to investigate the component stresses and interface interactions and modification of the performance analysis programs to permit use in the charge mode. During the last step, the hybrid simulator model was further modified to evaluate the selected phase-controlled rectifier augmentor.

The FCG-1 inverter is designed for a dc voltage range of 1.3 to 1 and for discharge operation only. The modifications required to adapt it to a battery requirement of a 1.6-to-1 dc voltage range and for charge and discharge operation were evaluated. It was concluded that the increased input filter and commutation capacitor sizes would require substantial modification to the existing bridge. The resulting design would have a 20-percent increase in size over the basic fuel cell bridge and would not have production commonality

with fuel cell inverters. Additionally, the overall converter efficiency was estimated to be 94.5 percent at end-of-charge and 89 percent at quarter-load start-of-charge. These are borderline to meet the efficiency goals of 95 percent average full load and 90 percent average one-quarter load (charge or discharge).

Based on these results, the program was directed toward the evaluation of changes to the basic system. Seven approaches to augmenting the converter derived from the FCG-1 inverter were screened, and two approaches selected for detailed examination - the use of a phase-controlled rectifier and the use of a boost regulator. Results of the examination are given in Table 1-1.

The phase-controlled rectifier approach was selected on the basis of the comparison shown in Table 1-2. The phase-controlled rectifier is the clear-cut choice for the 7-hour charge/10-hour discharge cycle because of its ability to increase the charge capability in this charge-limited cycle. For the 7-hour charge/ 5-hour discharge, the phase-controlled rectifier cost and efficiency advantage is small and approaches the accuracy of the estimates. The phase-controlled rectifier augmenter approach has lower complexity and lower development cost. For all of these reasons, the phase-controlled rectifier was selected as the augmentation approach.

TABLE 1-1. PHASE CONTROLLED RECTIFIER
VERSUS BOOST REGULATOR AUGMENTATION*

<u>System</u>	<u>Efficiency During Charge (%)</u>	<u>Relative Selling Price \$/kW</u>
Phase-controlled rectifier	96	1.0
Boost regulator	95.2	1.05

* For 7-hour charge/5-hour discharge and 1.7-to-1 dc voltage ratio

TABLE 1-2. FACTORS IN SELECTION OF PHASE-CONTROLLED RECTIFIER AUGMENTER

- Higher cycle efficiency
- Lower unit cost
- Increased system energy capacity for charge-limited cycles
- Optimum for both 7-hour/10-hour and 7-hour/5-hour cycles
- Reduced complexity
- Lower development cost and risk

Description of Selected System

One 9.2-MW module of the ac power-conditioner system, which employs the most attractive modification of the FCG-1 fuel cell power conditioner, is shown in Figure 1-1. It uses the basic FCG-1 system with minor modifications as the main battery converter element. The main diodes in the bridges are increased from 38 mm to 52 mm diameter, and the rating of the output magnetics is increased to make its rating in the charge-mode operation equal to the dc rating per module during the discharge mode.

Figure 1-1. Battery Power-Conditioning System

The phase-controlled rectifier used for augmentation is a standard two-bridge configuration. It is connected in series with the modified FCG-1 converter on the dc side, and is fed through its own transformer from the utility line at 13.8 kilovolts. The augments is used in the charge mode above 2860 volts dc input to increase the operating range of the modified fuel cell converter.

Efficiency

A power-conditioner system capable of operation over a 1.7-to-1 voltage range was evaluated for the 7-hour charge/5-hour discharge, and a second system capable of operation over a 1.6-to-1 voltage range was evaluated for the 7-hour charge/10-hour discharge cycle. Six battery cases (five advanced batteries plus a lead-acid case) were evaluated for each of the two cycles of interest using battery systems designed to match the power conditioner appropriate to the cycle. A digital computer analysis program was used to calculate the losses for various operating points in the discharge and charge cycle for each battery case. These were then integrated over the cycle to obtain average charge and discharge efficiencies.

The results of these calculations given in Table 1-3 show that the phase-controlled rectifier approach exceeds 95 percent average efficiency for both the charge and discharge cycles.

An investigation of one 7-hour/10-hour battery case for a 1.6-to-1 dc voltage range using a 1.7-to-1 voltage augments showed no difference in the charge cycle efficiency or the discharge cycle efficiency within the limits of accuracy of the calculations.

TABLE 1-3. POWER-CONDITIONER PERFORMANCE FOR ADVANCED BATTERY SYSTEMS*

<u>Battery System</u>	<u>Charge/Discharge, Hours</u>	<u>Charge Efficiency, %</u>	<u>Discharge Efficiency, %</u>
Sodium sulfur type 1	(7/5)	96.2	96.1
Sodium sulfur type 1	(7/10)	96.3	95.7
Sodium sulfur type 2	(7/5)	96.0	96.3
Sodium sulfur type 2	(7/10)	96.2	96.1
Lithium/metal sulfide 2	(10/5)**	95.8	96.2
Lithium/metal sulfide 2	(10/10)**	95.9	95.9
Lead acid	(7/5)	95.7	96.2
Lead acid	(7/10)	96.1	96.1
Zinc chloride	(5/5)**	96.1	96.2
Zinc chloride	(5/10)**	96.2	95.4
Sodium chloride	(7/5)	95.0	96.2
Sodium chloride	(7/10)	95.4	96.1

* For an energy storage system designed around a 27.6-MW power conditioner

** Alternative cycles indicated by battery manufacturers

Cost Estimation

The estimated selling price for the power conditioner for a 1.7-to-1 dc voltage range is 68.50 \$/kW and for a 1.6-to-1 dc voltage range is 67.50 \$/kW, based on the assumptions of this study. This estimate makes a number of assumptions concerning production quantity, manufacturing approach and manufacturing facility which are considered to be reasonable at this time. A revised estimate, reflecting specific assumptions should be made at the time any future firm hardware requirement is established. The cost goal of 60 \$/kW in 1975 adjusted to 1977 dollars is 68 \$/kW.

Summary

A power conditioner consisting of a converter derived from the FCG-1 inverter plus a phase-controlled rectifier is the most attractive approach in the use of the FCG-1 fuel cell inverter technology for electrochemical energy storage. This approach meets the cost and efficiency goals within the accuracy of the study. These studies also show that the design of a special augmentor for the 7-hour/ 10-hour cycle (1.6-to-1 voltage ratio) produces very limited benefits (1\$/kW in selling price and no efficiency improvement) and is therefore not recommended.

TASK 2 - DEMONSTRATION OF CONVERTER CHARACTERISTICS

The program for evaluation of self-commutated converters requires that the principal characteristics for battery application be demonstrated in megawatt-scale hardware. The demonstration was performed using an available 0.5-MW development converter system at PSD and supplemented with data from the 1-MW pilot inverter system. The 0.5-MW development converter system consists of two three-phase, 900 kW bridges together with 0.5-MW output magnetics. It was used in the early development of the self-commutated converter (3). The principal features demonstrated were:

- Ability to cancel lower-order harmonics in a low-voltage harmonic-cancellation transformer.
- Ability to operate through most ac system voltage transients and to commute off for all other system transients except severe lightning strokes under worst-case loading.
- Ability to supply continuously variable leading or lagging vars within the kVA rating of the machine during charge or discharge and at zero real power.

- Ability to operate at unity power factor without power factor correction capacitors.
- Ability to convert from the charge to the discharge mode without a dc polarity change.

Demonstration of Harmonic Cancellation

In a properly designed two-bridge system, the lower-order 5th and 7th harmonics are canceled. This ability was verified experimentally for several operating conditions, as shown in Table 1-4.

TABLE 1-4. DEMONSTRATION OF HARMONIC CANCELLATION

AC Power Delivered		Percent of Fundamental Voltage			
		<u>Fifth</u>		<u>Seventh</u>	
Side	HCT*	High Side		HCT*	High Side
	Input(%)	L-N(%)		Input(%)	L-N(%)
200 kW, PF = 1.0	36	0		46	0
200 kvar lead, PF = 0.0	19	0		33.5	0
200 kvar lag, PF = 0.0	63	0		49	0
-200 kW, PF = 1.0	60	0		54	0

NOTES:

*Harmonic cancellation transformer

Lead = Deliver vars to utility

Lag = Consume vars from utility

+kW = Inversion or discharge mode

-kW = Rectification or charge mode

L-N = Line to neutral

The data obtained from these tests verify the basic principles, but the voltage and current harmonic levels at the utility interface are higher than proposed for the full-scale power-conditioner system proposed for fuel cell application and selected in Task 1 (4). The full-scale systems utilize a three-bridge configuration while the 0.5-MW development system employs a two-bridge system without output filter. Use of three bridges eliminates the 11th and 13th harmonics present in the two-bridge system, and the 17th and 19th harmonics are the first to appear at the utility interface.

The ability of the self-commutated system to cancel lower-order harmonics reduces the requirements for an output filter to meet power quality requirements and consequently minimizes resonance with the utility network.

Demonstration of Operation through Transients

Experience from previous testing of the 0.5-MW development converter and the UTC 1-MW fuel cell pilot inverter system were used to demonstrate this feature. The 1-MW pilot inverter system had operated for 1022 hours in parallel with a 14.4 kV utility line. During this period, 106 voltage impulses superimposed on the normal ac waveform (exceeding 33 percent of nominal voltage) were experienced without service interruption. During the same period, 33 undervoltage events (less than 95 percent of nominal voltage) were experienced for at least one cycle. Of these 33 events, service was uninterrupted for 29, interrupted for 3 and automatically restarted when the utility line normalized, and switched once to a standby condition by the operator. The 0.5-MW development converter system experienced similar transient experience in 169 hours of operation without service interruption prior to this program. This feature minimizes interruptions of power flow to or from the battery system.

Demonstration of Var Supply Capability and Unity Power Factor Operation

The 0.5-MW system was operated at 180 kW, 0.9 power factor (PF), delivering vars, discharge and charge modes; 180 kW, 0.9 PF, consuming vars, discharge

and charge mode, and 200 kvar, 0 PF, consuming and delivering vars. This feature allows the use of the converter to control distribution system voltages and the power factor presented to the transmission line. These features reduce the cost of power factor correction and reduce transmission line losses.

It was also operated at 200 kW, unity PF in discharge mode (inversion) and at 200 kW, unity PF in charge mode (rectification). This feature reduces the requirement for power factor correction capacitors and their associated cost. It also minimizes resonance with the utility network.

Demonstration Of Rapid Reversal

The 0.5-MW system was switched from 200 kW charge to 200 kW discharge in less than 1/2 second, as shown in Figure 1-2(a). The test arrangement is shown in Figure 1-2(b). The ability to switch from charge mode to discharge mode without polarity reversal minimizes the cost of dc switchgear and permits rapid reversal. Rapid response may permit use of energy storage systems to improve area regulation and system stability.

Summary

This successful demonstration of the principal operating features of the self-commutated converter validates the technical feasibility of this approach for energy-storage applications.

A. CONVERTER WAVEFORMS

B. TEST ARRANGEMENT

Figure 1-2. Self-Commutated Power Reversal

TASK 3 - ISOLATED OPERATION SURVEY

The use of energy storage systems in an isolated operating mode provides increased service reliability for the area served. Operation of the system in

parallel with the utility line to reduce the peak demand or modify the power demand during critical periods may provide the potential for lower operating cost and increased flexibility. The purpose of the work under this task is to define the technical requirements.

The first step was to prepare a survey form defining the critical requirements. This survey form was sent to an initial group of five utilities selected in conjunction with and approved by the Department of Energy Program Manager. These utilities were then visited by PSD personnel and discussions were held concerning the application.

The utilities surveyed were small REA and municipal systems, as previous studies had indicated that large utilities with interconnected grid distribution systems would not benefit in general from the isolated operational capability.

The response experienced during the visits to the small utilities indicated that insufficient technical data existed at the majority of the utilities for the survey forms to be completed readily. One survey form was received from this group of five surveyed. The limited conclusions are drawn from the discussions and the one survey form.

Because of the limited response, it was decided to substitute three A&E firms for the remaining utilities to be surveyed. The results of this portion of the survey produced two packages of design data relating to the generation application of converter systems to small rural and municipal systems.

All parties surveyed expressed the opinion that a single representative specification for isolated operation would be impossible to write because of the differing application requirements. Three of the five utilities expressed favorable opinions regarding the use of battery energy storage in isolated operation, while all five were interested in fuel cell power plants for isolated operation.

The specific application of interest described by two utilities, including the one completing the survey form, was the use of a converter at the end of a long radial transmission line to provide emergency generation during outages. The one utility completing the form felt that the energy source should have a capability for 48 hours of operation. This requirement suggests the use of a primary power supply such as fuel cell system rather than a battery energy storage system.

In summary, the overall results of the survey were inconclusive with respect to the long-term requirements for energy storage systems in isolated operation because of the limited response. Insufficient results were obtained to prepare a technical specification of broad applicability. It appears that isolated operation must be considered on a case-by-case basis once battery and fuel cell systems are in commercial production.

SECTION 2

INTRODUCTION

SECTION 2. INTRODUCTION

PROGRAM OBJECTIVES

Electrochemical energy storage systems are under development for utility system use. The power conditioner, which converts the battery system output into a suitable form for utility system use and converts the utility system ac power into a suitable form for charging the battery, is a critical element in electrochemical energy storage systems.

The efficiency, cost, and reliability objectives for this application dictate the use of advanced solid-state semiconductor technology. The power levels of interest (tens of MW) narrow the choice to the use of the thyristor as the basic switching element. With the development of high power inverter-grade thyristors in the 1970's, MW level self-commutated converter technology warranted consideration on a viable power conditioning system approach.

The purpose of this program is to evaluate existing self-commutated converter technology for use in electrochemical energy storage systems including the Battery Energy Storage Test (BEST) facility. The specific equipment to be evaluated is the inverter being developed by United Technologies for use with its 27-MW FCG-1 fuel cell power plant. This inverter technology is used in the 4.8-MW Fuel Cell Demonstrator power plant. Only minor modifications of the equipment is permitted to maintain production commonality between battery and fuel cell systems.

The objectives associated with this purpose are: (1) to evaluate modifications required to permit the FCG-1 to operate in converter mode; (2) to estimate the characteristics of the modified FCG-1 as a converter; (3) to experimentally demonstrate the basic features of self-commutated converters; and, (4) to define a preliminary specification of converters for isolated operation.

PROGRAM APPROACH AND CONTEXT

The self-commutated converter technology evaluation has two major components: the evaluation of the cost and performance of a power conditioner system in an electrochemical energy storage system and the demonstration of the performance in MW-scale hardware. The evaluation of cost and performance of an existing self-commutated converter technology is based upon the use of the FCG-1 inverter system design. This system is designed for inverter mode operation only. This program determines the cost and performance of the most attractive modification for the electrochemical energy-storage application.

The demonstration of the performance of a self-commutated converter centers on its ability to switch rapidly from rectification to inversion without dc polarity reversal. This feature, along with other principal operating parameters, is investigated at UTC using a 0.5-MW development converter.

A third area of secondary interest is the ability of the self-commutated inverter system to operate isolated from the utility system. This feature would provide increased service reliability for an area served with an energy storage system. This program investigates the technical requirements for this type of operation.

The Electric Power Research Institute is sponsoring a related program, Research Project 841-1, AC/DC Power Converter for Batteries and Fuel Cells. The EPRI program(5) prepares an advanced converter design based on the FCG-1 inverter with improvements, such as advanced commutation circuits and 1980's thyristors. A coordinated approach is being used to maximize the benefits from United's FCG-1 inverter design, the DOE Program and EPRI RP841-1.

PROGRAM STRUCTURE

The program is broken down into three technical tasks. The overall program logic is shown in Figure 2-1.

Figure 2-1. DOE Program Logic Chart

Task 1 - Select Modification of FCG-1 Inverter

Under this task, the most attractive modification of the FCG-1 fuel cell inverter system is selected and a preliminary estimate of its characteristics is made. The task is structured as follows:

- Define electrical interface requirements based on available information describing storage battery characteristics.
- Expand present models of the inverter system to model converter operation.
- Estimate performance of FCG-1 fuel cell inverter modified for converter operation.

- (d) Review performance estimated in (c) with the project manager to determine its suitability for use in energy storage systems and recommend an approach for the remainder of the program.
- (e) If the performance is acceptable, prepare a conceptual design description of the converter system.
- (f) If the performance characteristics are not acceptable, evaluate changes to the basic system configuration. Identify, screen, and select best alternative approach(es) to be defined in sufficient detail to permit the estimates of cost, efficiency, and performance against requirements.

Task 2 - Test Self-Commutated Converter Features

Under this task, a test of the performance of converter control concepts is performed. This task is structured as follows:

- (a) Prepare a plan to test operation of self-commutated converter controls using an existing 0.5-MW system. Submit test plan for review.
- (b) Modify equipment and facilities.
- (c) Execute test plan. Compare system performance with predictions.
- (d) Define relevance of the test to the BEST facility and commercial operation.

Task 3 - Define Preliminary Specification for Isolated Operation

Under this task, the technical requirements for isolated operation of an energy system are defined. This task is structured as follows:

- (a) Define critical application requirements and prepare survey form.
- (b) Select eight individual utilities to be surveyed. Obtain DOE approval.
- (c) Survey four of the selected utilities.
- (d) Review results of survey of first four utilities and recommend changes.
- (e) Survey remaining four utilities.
- (f) Prepare a preliminary specification for isolated operation.

SECTION 3

RESULTS AND CONCLUSIONS

SECTION 3. RESULTS AND CONCLUSIONS

TASK 1 - SELECTION OF FCG-1 INVERTER MODIFICATION

Phase-Controlled Rectifier Augmenter Selected

The most attractive modification of the FCG-1 inverter system for use in electrochemical energy storage systems was selected under this task. This system can operate as a converter and perform the two primary functions required to charge and discharge advanced energy storage batteries employed within a utility system. During the battery charge cycle, the ac power supplied from a utility line is rectified into dc power, which is applied to the storage battery. During the battery discharge cycle, unregulated dc power is inverted into regulated ac power, which can be dispatched into a utility line.

The initial step of the task was identification of the electrical interface characteristics, based on a survey of six advanced-battery manufacturers. Results were obtained on the following advanced batteries: sodium-sulfur (two types), sodium-antimony trichloride, zinc-chlorine, and lithium/metal sulfide (two types). A summary of this information is presented in Table 3-1. A detailed discussion of the battery characteristics are given in Appendix A3. The two battery cycles given principal consideration based on the results of the survey are the 7-hour charge, 10-hour discharge cycle and the 7-hour charge, 5-hour discharge cycle. The battery voltage characteristics for the 7-hour charge and 10-hour discharge cycle can be summarized as follows:

- A. Maximum voltage ratio for end-of-charge to end-of-discharge of 1.6:1 satisfies all batteries surveyed except for the lithium/metal sulfide type 1, which has a voltage ratio of 2.06:1.
- B. A maximum voltage ratio for start-of-discharge to end-of-discharge of 1.30:1 satisfies all batteries surveyed except lithium/metal sulfide type 1, which has a ratio of 1.7:1, and sodium chloride, which has a ratio of 1.35:1. The 1.35:1 voltage ratio of the sodium chloride

battery can be reduced to 1.30:1 with a negligible effect on the available energy during discharge.

TABLE 3-1.
RELATIVE VOLTAGE RANGES AS A FUNCTION OF DISCHARGE AND CHARGE CYCLES

Discharge Hrs.	Charge Hrs.	Discharge Voltage Range*							Charge Voltage Range*							Maximum Voltage Range*						
		1	2	3	4 ¹	5 ²	6	7	1	2	3	4 ¹	5 ²	6	7	1	2	3	4 ¹	5 ²	6	7
3	7	1.42	1.17	1.26	1.11	1.71	1.30	1.06	1.19	1.13	1.42	1.33	-	1.14	1.46	1.91	1.65	1.74	1.33	2.79	1.60	1.46
5	7	1.31	1.11	1.30	1.11	1.8	1.27	1.20	1.32	1.18	1.42	1.24	1.36	1.14	1.42	1.69	1.30	1.63	1.24	2.37	1.60	1.42
10	7	1.25	1.11	1.30	1.11	1.73	1.27	1.18	1.34	1.13	1.45	1.21	1.39	1.14	1.38	1.53	1.25	1.47	1.21	2.06	1.60	1.38

*Range is expressed as the ratio of voltage at end of period to start of period.

(1) Type 4 ratios are for 3-hr. discharge/3-hr. charge-5-hr. discharge/5-hr. charge-5-hr. discharge/10-hr. charge.

(2) Type 5 ratios are 10-hr. charge.

Battery Type No.	Description	Typical Operating Temperature (°C)
1	Sodium Sulphur Type 1	300-350
2	Sodium Sulphur Type 2	300-350
3	Sodium Chloride	300-400
4	Zinc Chloride	25-50
5	Lithium Metal Sulphide Type 1	400-500
6	Lithium Metal Sulphide Type 2	400-500
7	Lead Acid	20-30

The battery voltage characteristics for the 7-hour charge and 5-hour discharge cycle can be summarized as follows:

- A. A maximum voltage ratio of end-of-charge to end-of-discharge of 1.7:1 satisfied all the batteries surveyed except for the lithium/metal sulfide type 1, which has a ratio of 2.4:1.
- B. A maximum voltage ratio for start-of-discharge to end-of-discharge of 1.3:1 satisfies all the batteries surveyed except for the lithium/metal sulfide type 1, which has a ratio of 1.8:1.

Based on these results, 1.7-to-1 and 1.6-to-1 dc voltage ratios were selected for the charge ratio voltage design values for the two cycles. A maximum value of 1.3 to 1 was selected for the discharge cycle. The dc voltage range required is dependent on the battery type and the ratio of charge time to discharge time. The fuel cell inverter is designed for a dc voltage range of 1.3 to 1 during the discharge mode of operation. Therefore, modification of

the fuel cell power inverter system was necessary to meet the battery system-wide voltage range requirements during the charge cycle.

Initially, a modified FCG-1 power conditioner capable of independently operating over the 1.6-to-1 dc was evaluated. The analysis of this approach revealed that:

- Modification of the FCG-1 bridge for operation over a 1.6-to-1 voltage range will increase the bridge size 20 percent. The increased input filter and capacitor sizes cannot be incorporated in the bridge without substantial modifications.
- The efficiencies are summarized in Table 3-2. Load settings were chosen for screening purposes and reflect the worst case conditions expected. This approach is borderline for the efficiency goals of 95-percent average full load and 90-percent average quarter-load (charge or discharge mode).

TABLE 3-2. CONVERTER EFFICIENCY FOR THE MODIFIED FCG-1 SYSTEM (1.6:1 VOLTAGE RANGE)

<u>Mode</u>	Operating Conditions					
	<u>Start of Charge</u>	<u>End of Charge</u>	<u>Start of Discharge</u>		<u>End of Discharge</u>	
Voltage, dc	2850	3520	2860		2200	
Power level, %	100	100	100	25	100	25
Overall efficiency, %	95.3	94.5	95.2	89.0	95.9	92.7
Program efficiency						
Goal, %	95.0	95.0	95.0	90.0	95.0	90.0

Based on these results, which would be accentuated at the 1.7-to-1 voltage range, the program was directed toward the investigation of augmented approaches. Since the basic FCG-1 system is designed for operation over a

1.3-to-1 range (2200 to 2860 Vdc) and the upper limit voltage cannot be exceeded without component overstress, the augmentation approach should reduce the converter system dc input voltage to a value within this range for all operating conditions. Operation of the system at reduced power at lower voltages is also permissible.

The augmentation concepts considered were as follows:

- Line-commutated converter
- Self-commutated converter
- Buck/boost and boost/boost regulator
- Boost regulator
- Phase-controlled rectifier
- Dual fuel cell converter bridges
- Battery cell stack switching

These approaches were screened for the 7-hour/5-hour cycle (1.7-to-1 dc voltage ratio) and the 7-hour/10-hour cycles (1.6-to-1 dc voltage ratio). The 7-hour/5-hour cycle is a discharge capacity-limited cycle because the power level during discharge is greater than that during charge. Therefore, concepts that provide maximum inverter capability with the lowest cost increase over the basic converter system are favorable. The phase-controlled rectifier and boost regulator systems were selected on the basis of this criterion.

Since the kW rating during the charge portion is greater than during the discharge period, the 7-hour/10-hour cycle is a charge-limited cycle. Therefore, concepts that provide maximum rectification capability with the lowest cost increase over the basic converter system are favorable. The phase-controlled rectifier was selected based on preliminary screening. Its capability to provide additional rectification capacity during the charge cycle makes it superior to the boost regulator for this cycle.

A detailed evaluation of the two candidates for the 7-hour/5-hour cycle and the single candidate for the 7-hour/10-hour cycle was made. During this evaluation period, the use of dual bridges (two sets in parallel) was re-examined for both cycles on a more detailed basis. Reexamination of the dual-bridge approach showed that for the 7-hour/ 5-hour cycle, the average cycle efficiency was approximately the same as the phase-controlled rectifier and the cost of the phase-controlled rectifier on a kW-hr delivered basis was 13 percent lower. For the 7-hour/ 10-hour cycle, the phase-controlled rectifier was 20 percent lower in cost and again the cycle efficiency was approximately equal. The selection of the phase-controlled rectifier over the dual FCG-1 bridge concept was retained.

The relative cost estimates of the two principal concepts for the two cycles is summarized in Table 3-3. The boost regulator approach was not examined in detail for the 7-hour/10-hour cycle because it does not increase the kW level during the charge cycle and was therefore eliminated in the preliminary screening.

TABLE 3-3. AUGMENTED CONVERTER SELLING PRICE

<u>System and Cycle</u>	<u>Relative Selling Price \$/kW</u>
7-hour/5-hour cycle	
Phase-controlled rectifier	1.0
Boost regulator	1.05
7-hour/10-hour cycle	
Phase-controlled rectifier	0.98

Since the efficiency of the two approaches would be the same during the discharge cycle, a high-power point and a lower-power point, during taper

charge, were chosen for comparison. The results are summarized in Table 3-4.

TABLE 3-4. EFFICIENCY COMPARISON OF AUGMENTATION CONCEPTS

Battery Conditions		Power-Conditioning System	
<u>During Charge</u>		<u>Efficiency, %</u>	
MW	Volts	Phase-Controlled Rectifier Augmentation	Boost Regulator Augmentation
6.5	3100	96	95.2
1.8	3600	88.9	89.5

The phase-controlled rectifier is slightly more efficient for the high-power operation. During the taper-charge period, it is slightly less efficient. The taper-charge period exists only for certain batteries for a relatively short period of time; therefore, on an entire charge-cycle basis, the phase-controlled rectifier approach will be more efficient.

The phase-controlled rectifier was selected for detailed consideration based on the following:

- Higher overall cycle efficiency
- Lower cost
- Lower development cost and risk
- Reduced complexity
- Increased system energy capacity for charge-limited cycles
- Optimum for both cycles considered

Functional Description

The configuration selected to meet the battery energy storage requirement is a FCG-1 inverter modified for converter operation with a phase-controlled rectifier augments. The system is rated 27.6-MW ac discharge into the utility line and consists of three 9.2-MW modules. Since the modules are identical, the system description is based on one 9.2-MW module of the 27.6-MW system.

The power-conditioning system is depicted in Figure 3-1. It consists of the following elements: the self-commutated converter, the phase-controlled rectifier, dc switchgear, ac switchgear, lightning arrestors, controls, and instrumentation. The converter system consists of three self-commutated bridges, series reactors, harmonic-cancelling transformers, and an output transformer. The phase-controlled rectifier consists of two three-phase rectifier bridges, a transformer, and bypass switchgear.

Figure 3-1. Battery Power-Conditioning System

This power-conditioning system converts dc from the battery system to three-phase, 60-Hz ac power at distribution voltage level during the discharge portion of the battery cycle and converts three-phase, 60-Hz ac power to dc during the charge portion of the battery cycle.

During the discharge cycle, the phase-controlled rectifier is bypassed through an internal switch and the converter performs the conversion of the dc output of the battery to ac utility power. In this mode, the unregulated battery output voltage is fed to three self-commutated inverter bridges that convert it into a three-phase ac modulated quasi-squarewave voltage. The output voltages of the inverter bridges are phase displaced by 20 degrees and fed into the harmonic-cancelling transformers. All harmonic voltages up to the 17th are eliminated from the output.

The output of the harmonic cancelling transformers is combined and stepped up to the voltage level of the utility line by means of a nearly standard utility output transformer. Series reactors are connected between the inverter bridge and the harmonic-cancelling transformer to provide an additional inductive impedance to the utility line for control purposes. Appropriate ac and dc switchgear and fuses are provided for isolation and fault protection.

Operation during the charge cycle may be divided into two phases. The converter section is limited to operation in the rectification mode between 2200 and 2860 volts. During this period, the ac output of the utility line is stepped down to a lower voltage and separated into three outputs in the output transformer. The harmonic-cancelling reactors eliminate voltage harmonics on the utility line in a manner similar to that of the inversion mode. The series reactors perform a similar control function to inversion-mode operation. The quasi-squarewave ac output voltage appearing at the bridges is converted to dc by the rectification-mode operation of the bridges.

During operation above 2860 volts, operation of the phase-controlled rectifier is required. Ac from the utility line is transformed into two low-voltage, three-phase outputs displaced 30 electrical degrees from each other. These

are fed through two three-phase thyristor bridges of the phase-controlled type. These bridges are connected in parallel on the output and provide a series voltage that is added to the output of the modified fuel cell converter to provide the difference between the maximum 2860 output voltage of this system and the battery voltage. The output voltage of the phase-controlled rectifiers is varied by modifying the phase angle of the thyristors in the three-phase bridges.

Interface Specification

Selected interface requirements and ratings for the selected power conditioner are summarized in Table 3-5 for one 9.2-MW module of the 27.6-MW system.

TABLE 3-5 . DC AND AC INTERFACE SPECIFICATION*

DC Interface

Maximum voltage	
Charge cycle	3740 volts
Discharge cycle	2860 volts
Minimum voltage	
Charge cycle	2200 volts
Discharge cycle	2200 volts
Maximum continuous rating	
Charge cycle	
without augments	9.6 MW
with augments	12.6 MW
Discharge cycle	9.6 MW

AC Interface

Voltage	13.8 kV, 3-phase
Frequency	60 Hz
Line voltage variation	+5% to -5% normal
Maximum line voltage unbalance	+10% to -20% emergency
Total harmonic voltages	4% of fundamental
Maximum rms fault current	110% rated
Maximum continuous rating	
Charge cycle	
without augments	10 MVA at 1.0 pf
with augments	13.1 MVA at 1.0 pf
Discharge cycle	9.2 MVA at 1.0 pf
Operating range kw	0 to 100% rated power
kvar	to rated kVA

* Values given are for 1.7-to-1 voltage ratio system

System Design

Converter - The converter design is similar to the design employed for the FCG-1 inverter system with the exception of two modifications incorporated to yield a higher power capability during the charge mode of operation. Several internal power handling components establish different maximum limits for this power capability in the fuel cell inverter. Modification of the commutation diode and output magnetics, which maintains the high degree of production commonality required, allowed the establishment of a charge power base of 10 MW ac. The required modification of the output magnetics was minimal in increasing its power capability. The commutation diode modification consisted of changing the device from 38 mm to 52 mm to satisfy the power demand and increasing the cooling capacity to satisfy the additional loss incurred.

Phase-Controlled Rectifier - The design techniques employed were similar to those used in the design of the fuel cell inverter. These techniques included analytical calculations, digital computer programs, and verification of performance and component stresses through the use of the EAI hybrid simulator. The augments is employed during the charge cycle only as the system voltage excursions during the discharge cycle are within the modified fuel cell converter capability. Table 3-6 identifies the ratings and interface characteristics of the phase-controlled rectifier augments developed for the 1.7-to-1 voltage ratio.

TABLE 3-6. AUGMENTER CHARACTERISTICS

AC Input

Voltage	13.8 kV, 3-phase
Maximum continuous power	3.1 MVA

DC Output

Voltage (maximum)	880 Vdc
Maximum continuous power	3.0 MW
Voltage range	0 to 880 Vdc

The selection of a six-pulse parallel bridge configuration allowed the use of standard, production-type, phase-controlled rectifier bridges in conjunction with a standard delta-wye transformer. The series inductors were designed to limit the maximum surge current during a false firing of the bridge thyristors to a level below the capability of the devices employed. The hybrid simulator was used to verify that this value of inductance limited the rms ripple current in the battery source to less than 10 percent of the full rated current as specified. A dc-bypass switch and force-down network were used to facilitate the transition between the various modes of operation. Two three-pole ac contactors were incorporated to allow disconnection of the ac source from the augments.

Design Description

The battery converter system consists of the following major subsystems and components:

Converter

- Three converter bridges

- Three series reactors

- Harmonic-cancelling magnetics consisting of a phase shifting transformer and a summing transformer.

- Output transformer

- Logic and controls

Phase-controlled Rectifier Augments

- Two rectifier bridges

- Augments transformer

- Down-forcing network

- AC contactors

- Bypass contactor

- AC switchgear and protection

- DC switchgear

These subsystems and components as shown in Figure 3-2 are described in the following sections:

Figure 3-2. Augmented Converter Block Diagram

Converter Bridge - Each bridge as shown in Figure 3-3 is forced-air cooled and packaged in its own frame with acoustical enclosure. Each bridge consists of the following:

- a) Three series inverter-grade power thyristors and snubber circuits per switch (18 total devices per bridge). These 67-mm inverter-grade devices are rated at 1800 volts and 1200 amperes average. The voltage margins for the main thyristors are established based upon a worst case combination of a steady state and transient voltage stress occurring simultaneously. The transient stress level is a function of circuit design parameters and is adjusted to provide adequate voltage margin while maintaining high efficiency. This

design has a voltage margin of 35 percent, as compared to the 15 percent minimum value considered adequate.

b) Two series commutation thyristors and snubber circuits per switch (12 total devices per bridge). These are 38-mm devices rated 1400 volts and 650 amperes average.

Figure 3-3. Simplified Schematic of Three Phase Converter Bridge

- c) Three series main diodes and snubber circuits per switch (18 total per bridge). These are 52-mm devices rated 1800 volts and 1100 amperes average.
- d) Three sets of commutation capacitors (30 total per bridge). They are oil-filled, ac capacitors rated at 13.7 microfarads, 6000 volts peak-to-peak, and 120 amperes rms.
- e) Three sets of commutation inductors per bridge. These are Litz wire-wound, air-core inductors rated at 800 amperes rms.
- f) Twelve input filter capacitors per bridge. These are oil-filled, dc filter capacitors rated at 457 microfarads, 120 amperes rms, and 4000 volts dc.

Series Reactors - There are three series reactor assemblies. Each assembly has three class-A/FA inductors. Each inductor is rated 325.8 microhenries and 1210 amperes rms. These inductors provide 16 percent impedance between the inverter output and the utility line. This impedance, together with an additional 1 percent in the harmonic-cancelling transformers and another 5 percent in the output transformer, provides a total of 22 percent to limit surges and permits control of real and reactive output power.

Harmonic-cancelling Transformers - These two transformers take the modulated quasi-squarewave outputs from the inverter bridges and remove the harmonics, providing a low-distortion, 60-Hz sine wave from the output transformer. Each of these units is a three-phase, multiple-winding, class-A/FA, dry-type transformer.

Output Transformer - The output transformer, which boosts the power plant output to utility line voltage, is a three-phase, 60-Hz, oil-filled, pad-mounted transformer. It is 110-kV BIL design, class-OA/FA rated

10,000 kVA, 13,800 volts high side, and 2000 volts low side. The transformer consists of four windings: a wye-connected high-side winding and three low-side delta windings. The transformer includes an external manually operated no-load tap changer for high-voltage taps to permit $\pm 2\frac{1}{2}$ percent and ± 5 percent adjustment of high-side rated voltage.

Phase-controlled Rectifier Augmenter - The two rectifier bridges, two series inductors, force-down thyristors, two ac contactors, and the dc-bypass switch are packaged in a single frame.

- Each rectifier bridge has two series power thyristors and snubber circuits per switch (12 total devices per bridge). The thyristors are 52-mm size rated at 2400 volts and 1000 amperes average.
- The two series pass diodes are 33-mm devices rated at 2000 volts and 1000 amperes average.
- The two series inductors are each rated at 447 microhenries and 1700 amperes.
- The two force-down thyristors are 52-mm size and rated at 2400 volts and 1000 amperes average.

The augmenter transformer is an OF/FA class transformer rated at 3.2 MVA. The transformer consists of three windings: a wye-connected high-side winding, a delta low-voltage winding, and a wye low-voltage winding.

DC Protection - The dc protection provides automatic current-limiting interruption of the dc line between the battery system and the power conditioner in the event of a fault. This is accomplished by means of separate interrupt devices on the positive and negative line. When the

devices interrupt the normal current path, the fault current is transferred into a special high-voltage fuse, which then interrupts the arc. This dc protection device has three types of current sensing and control: maximum current, rate-of-current rise, and an inverse time-current characteristic. It will interrupt 3500 volts per pole and clear within several milliseconds. The dc protection system also includes a mechanical isolation switch for no-load disconnect during startup/shutdown and maintenance or checkout.

The component is currently under development for the 4.8-MW Fuel Cell Demonstrator Inverter System. Additional development will be required to uprate it to the battery application.

AC Breaker - The ac breaker is a 13.8-kV, metalclad draw-out circuit breaker with controls and protection. The breaker is rated 1200 amperes rms, 15 kV with an interrupting capability of 560 MVA. It provides overcurrent protection in the event of a fault in the converter magnetics.

Control Logic and Protection - The control logic and protection circuitry provides proper gating of inverter thyristors, maintains dc circulating currents within limits, provides for synchronizing to utility line, and utilizes closed-loop regulation for stable control of real and reactive power levels. It automatically responds to protective functions, out-of-limit operating conditions, and provides auto start/stop sequences. The control logic for the phase-controlled rectifier is incorporated in the modified fuel cell converter assembly. The control logic assembly consists of a free-standing cabinet containing power supplies, printed circuit logic cards, relay rack, internal wiring, input/ output connector interfaces.

The controls have several levels to obtain high reliability and facilitate troubleshooting and repair. Completely interchangeable digital circuit cards are used on the pole, bridge, and module level. About one-third of the cards in the module logic are associated with generation of the

gating signals for the nine power poles from the output of the phase and voltage controllers. The remainder of the cards involve regulation, sensing, sequencing, and protection.

Controls hardware additions for battery applications include current controller interface to regulator, rectifier and crowbar (shorting) thyristor gating, and interface sequencing. About three or four cards per module are expected to be needed. Standard logic power supplies and cabinets used in fuel cell inverters can accommodate this increase in cards. The power conditioner includes lightning arrestors.

Mechanical Layout

In the present mechanical design concept for the FCG-1, as implemented in the 4.8-MW Fuel Cell Demonstrator inverter system presently under construction, the power conditioner components are factory-assembled within a weatherproof enclosure that is configured as two truck-transportable pallets. These pallets are shipped individually and connected at the site. The battery converter power conditioner is shown in Figure 3-4 as a modified version of this basic concept. In a mature production version, it is envisioned that a higher degree of integration of the components and pallet structure will be achieved. The major components of the power-conditioning system and their locations are listed in Table 3-7. The footprint for this unit is 1432 ft² including 8 foot access on all sides.

Figure 3-4. Arrangement of Converter Power-Conditioner System Components

TABLE 3-7. MAJOR COMPONENTS OF THE POWER-CONDITIONING SYSTEM

<u>Component</u>	<u>Pallet Location</u>
Three inverter bridges	A
Inverter logic and controls	A
Three series reactors	B
Augmenter	A
One phase-shifting transformer	B
One summing transformer	B
AC breaker	B
Output transformer	Separate
Augmenter transformer	Separate
DC Protection	Separate

The assembled power conditioner has provisions for heating, cooling, and ventilation.

Operation and Control

The control system (Figure 3-5) performs a variety of functions to dispatch requested watts and vars to the utility line during discharge of a battery or to provide dc charging power at proper dc voltage and current and requested ac power factor during charge. The master converter controller monitors input requests from the site controller and from conditions of all electrical parts of the power plant, including source, converter output, and utility line voltages. The status of the electrical systems is transmitted to the site controller so that overall power plant operating decisions may be made.

Startup - When the module controller determines that all parameters are within operating range, a request to operate from the site controller is accepted. The source is then activated as the first step in the start sequence. The additional steps to bring the system on line are: (1) close charging circuits to

charge the input filter capacitors to dc bus voltage; (2) close ac breaker; (3) close the main dc disconnects; (4) turn on the converters by gating the thyristors. This sequence takes place in approximately 30 seconds. The unit is now ready to receive a command for discharge or charge.

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Figure 3-5. Functional Block Diagram for Battery Operation

Operation In Discharge Mode - Upon receipt of a command from the dispatcher, module controllers set individual converters to power and var levels set by master control. In the module controller, a feedback controller maintains selected phase angle differences between the converter bridge output fundamental voltage and the utility line. A second feedback controller maintains a selected voltage difference between the converter bridge output fundamental voltage and the utility line. A feedback regulator system selects and maintains the phase angle and voltage difference settings required to produce the real and reactive power required to satisfy the battery profile and the dispatched command.

Under normal operation, control of power and var levels is accomplished by operating the converters at phase angle and voltage differences from the utility line. Levels are limited by two factors: the MVA capability of the converter and the power range of the source. The converter can operate at any power angle. The continuous phase angle and voltage difference ranges of the controller is large enough to set full power flow in either direction.

Operation in Charge Mode - Monitoring of the dc current is required in the charge mode. Charge-mode operation is divided into two portions - operation with the converter, and operation with the phase-controlled rectifier augmenting the converter. Augmentation is required above the 2860-volt maximum operating capability of the FCG-1 derived converter.

Operation with the converter is similar to operation in the discharge mode previously described.

The transition to augmented operation is accomplished as follows:

1. The dc-bypass switch across the phase-controlled rectifier input is opened when the dc bus reaches 2860 volts. The current then transfers to the bypass diode.
2. The phase-controlled rectifier (PCR) is fired at an angle retarded 90 degrees from full conduction, giving zero output from the augments.
3. The PCR thyristor conduction angles are increased until the bypass diode is forward-biased and the PCR is handling the full converter current.
4. The thyristor conduction angle is increased at a programmed rate until full output voltage is reached. Since the converter is operating in the current-limiting mode, its input voltage will drop to provide the difference between the battery voltage and the 880 voltage output of the phase-controlled rectifier.

5. The current into the battery is now regulated by controlling the phase angle of the modified fuel cell converter with respect to the utility line. The PCR voltage is maintained at full output and operates at near-utility power factor. Control of vars is accomplished by controlling the voltage of the converter with respect to the utility line.

Normal transition from augmentation occurs after the battery has been fully charged, is in the quiescent state, and discharge operation is desired. In this case, the battery voltage is below 2860 volts and the modified fuel cell converter is started in the normal manner.

Should a request for battery discharge operation occur because of utility needs, fast operation is possible. With the rectifiers out of the circuit, slewing time to respond to the dispatcher's command is on the order of 250 milliseconds between charge and discharge. If a discharge request occurs when the rectifiers are in operation:

1. The down-forcing network is turned on, and the converter is switched to discharge operation at a current value slightly less than the rated current value of the down-forcing resistor.
2. The output voltage of the phase-controlled rectifier is reduced in a programmed manner until zero output volts are reached. The converter current is also maintained at a value less than the current in the down-forcing resistor.
3. The dc contactor is closed when the dc bus voltage is 2860 volts or less and the voltage across the contactor is less than 100 volts.
4. The converter is then ramped up to the programmed discharge power.

The transition from augmented operation to converter only is dependent upon the interaction of the down-forcing network and the battery parameters. A more detailed investigation with better definition of the battery parameters is required to determine the actual transition times and voltage.

Normal shutdown is accomplished by inhibiting thyristor gates, opening all breakers, and placing the source in standby mode or deactivating as requested.

Abnormal Operation and Protection - Both the master controller and the module controller monitor the utility line. For small line variations, the master controller may lower the vars or power to keep the system in operation. In the case of large changes such as line faults or lightning, the module controller may shut off the converter to avoid reaching the maximum capability of the commutation circuits. The parameters governing the decision are load current and the magnitude, duration and rate of change of line disturbances. As conditions return to normal on the line, the converters are restarted. There is a delay of about 100 milliseconds on restart to allow stabilization of converter circuitry.

The following out-of-limit signals will cause a power conditioner subsystem (PCS) interrupt:

- DC undervoltage (DCUV)
- DC overvoltage (DCOV)
- Phase overcurrent (CLP)
- AC overvoltage (ACOV)
- AC undervoltage (ACUV)
- Loss of ac line synch (SLP)
- AC line voltage unbalance

Note: A PCS interrupt means that the inverter is immediately shut down momentarily and then restarts with all converter

switchgear remaining closed. If the problem is transient, the system will restart and continue normal operation. If the problem persists, the logic is programmed to attempt three restarts. After the third restart attempt, the inverter remains off and the battery plant is automatically put in standby, and all converter switchgear is opened.

The following will cause a PCS shutdown and place the battery plant on standby:

- Loss of inverter cooling fans (OTP)
- Any blown pole fuse (FVP)
- DC interrupter open
- AC breaker open
- Three PCS interrupts
- Loss of control power
- Loss of dual power supply in logic (LGP)

Operating Characteristics

The operating characteristics of the battery power-conditioning system were analyzed using The Electronics Associates, Inc. Hybrid Computer, which incorporates an analog model of the system. A block diagram of the system as implemented on the simulator is given in Figure 3-6. The analog/digital computer allowed system simulation under typical operating conditions at various ac load and dc voltage levels. The conditions evaluated are presented in Table 3-8. These representative cases were selected to reflect the effects of ac load levels, dc voltage, and the use of supplemental augmentation. The previously developed hybrid model of the fuel cell power conditioner was modified to allow evaluation of the system as a converter. Additional modification of the model was required to incorporate the phase-controlled rectifier augments. The current and voltage waveforms presented to the ac and dc interface buses were of primary interest. Internal component stresses of the converter and augments were also analyzed. The data generated by the

simulator included the waveform plot of each parameter of interest (either voltage or current), a harmonic analysis of the waveform, and a stripchart recording depicting several cycles of the waveform during steady-state operation. Figures 3-7 and 3-8 provide a representative set of data for the battery current with the augments in operation at a 10-MW ac power level. Figure 3-7 shows the battery current waveform over 360 electrical degrees of a 60-Hz cycle. The major ripple frequency of the battery current is 12 times the 60 Hz fundamental. Figure 3-6 shows the frequency spectrum of the battery current waveform. The amplitude of each harmonic is presented. Each harmonic is also expressed as a percentage of the dc current level. The analysis with the hybrid simulator has been verified with laboratory testing for previous system designs. The analysis performed for the seven cases ensured that the rms ripple current in the battery source did not exceed the 10 percent of full-load current as specified, the power conditioner operation did not adversely affect the utility system, and the system functioned as predicted. Examination of selected current and voltage waveforms over the range of operating conditions confirmed that the design rating of the following components were not exceeded:

- Converter Bridge
 - Power Thyristors
 - Commutation Thyristors
 - Main Diodes
 - Commutation Capacitors
 - Commutation Inductors
 - Input Filter Capacitors
- Series Reactor
- Harmonic-Cancelling Reactors
- Output Transformer
- Phase-Controlled Rectifier Augments
 - Rectifier Bridges
 - Rectifier Transformer

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Figure 3-6. Block Diagram of Augmented Power-Conditioner System

TABLE 3-8. HYBRID COMPUTER TEST CONDITIONS FOR BATTERY POWER-CONDITIONING SYSTEM SIMULATION

<u>Mode of Operation</u>	<u>Augmentation Employed</u>	<u>DC Voltage, Volts</u>	<u>Augmentation Voltage, Volts</u>	<u>AC Power, MW</u>
DISCHARGE	NO	2200	N/A	9.2
DISCHARGE	NO	2860	N/A	2.7
CHARGE	NO	2860	N/A	10
CHARGE	YES	2860	0	10
CHARGE	YES	2860	660	10
CHARGE	YES	2860	660	2.7
CHARGE	YES	2860	330	10

Figure 3-7. Battery Current Waveform

HARMONIC	AMPL	PERCENT			
0 (DC)	4736	100.0000	31	0003	0719
1 (60 Hz)	0101	2.3431	32	0003	0719
2	0001	1.8742	33	0003	0719
3	0052	1.1991	34	0003	0582
4	0032	0.6997	35	0003	0719
5	0028	0.5944	36	0010	2257
6	0030	0.6447	37	0004	0823
7	0018	0.4270	38	0003	0582
8	0016	0.3679	39	0003	0760
9	0013	0.3107	40	0003	0760
10	0012	0.2825	41	0002	0446
11	0011	0.2635	42	0002	0446
12	0101	2.3279	43	0003	0582
13	0011	0.2524	44	0003	0582
14	0009	0.2190	45	0003	0719
15	0009	0.1995	46	0003	0719
16	0007	0.1716	47	0003	0719
17	0009	0.1980	48	0005	1129
18	0010	0.2402	49	0002	0446
19	0004	0.1027	50	0002	0446
20	0005	0.1163	51	0002	0446
21	0005	0.1137	52	0002	0446
22	0004	0.0998	53	0002	0446
23	0005	0.1137	54	0002	0446
24	0023	5.222	55	0002	0446
25	0005	0.1137	56	0002	0446
26	0004	0.0946	57	0002	0446
27	0004	0.0946	58	0002	0446
28	0004	0.1027	59	0002	0564
29	0004	0.0692	60	0003	0719
30	0003	0.0719	61	0002	0399
			62	0002	0446
			63	0002	0446
			64	0001	0315

CONDITIONS
 10 MW ac IN CHARGE MODE
 660 Vdc AUGMENTER VOLTAGE
 1.6 TO 1 dc VOLTAGE RATIO DESIGN

AMPL = AMPLITUDE OF HARMONIC IN
 PU, 1.0 PU = 8000 AMPS
 PERCENT = HARMONIC AMPLITUDE
 EXPRESSED AS FUNCTION OF dc LEVEL

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Figure 3-8. Battery Current Waveform Harmonics

Cost Estimation

System costs were estimated on the basis of 50 27.6-MW systems (150 converter modules) manufactured in 1982. These costs are stated in 1977 dollars. This estimate makes a number of assumptions concerning production quantity, manufacturing approach, and manufacturing facility which are considered to be reasonable at this time. A revised estimate, reflecting specific assumptions should be made at the time any future firm hardware requirement is established. The system costs included the modified FCG-1 power conditioner and either the 1.6-to-1 or the 1.7-to-1 dc voltage range phase-controlled rectifier augmentor. The estimated selling prices are based on a 9.2-MW discharge rating and are summarized as follows:

<u>System</u>	<u>\$/kW</u>
Modified FCG-1 Power Conditioner with	
1.6-to-1 phase-controlled rectifier	67.5
1.7-to-1 phase-controlled rectifier	68.5

This compares to a goal of 60\$/kW in 1975 dollars adjusted to \$68/kW in 1977 dollars.

The basic estimates did not include palletizing costs. Also, these costs are felt to be conservative in the areas of mechanical component costs and labor requirements because they were based on experience with the fabrication of the 4.8-MW Demonstrator and did not fully reflect the economics of a mature production situation. The savings resulting from production economies are expected to offset the palletizing costs.

Efficiency and Discharge Energy Capacity

The cycle efficiency for the augmented power-conditioning system was determined through the use of a performance analysis computer program. The loss-calculation techniques employed were identical to methods that have been

proved through laboratory testing of previous power-conditioner designs. For all battery profiles evaluated, the power-conditioning system efficiency exceeded the program goals of 95 percent average at full load and 90 percent average at quarter-load. The charge and discharge cycle efficiencies of the power-conditioning system are presented in Table 3-9 for each of the advanced energy storage batteries. In the above analysis supplemental augmentation was employed whenever the battery voltage exceeded the maximum operating voltage of the modified fuel cell converter (2860 Vdc). The efficiencies given are the converter efficiencies for the charge and discharge period and do not include the battery efficiency.

TABLE 3-9. AUGMENTED POWER-CONDITIONING SYSTEM PERFORMANCE

Battery System	Charge/ Discharge, Hours	Charge Efficiency, %	Discharge Efficiency, %
Sodium sulfur type 1	(7/5)	96.2	96.1
Sodium sulfur type 1	(7/10)	96.3	95.7
Sodium sulfur type 2	(7/5)	96.0	96.3
Sodium sulfur type 2	(7/10)	96.2	96.1
Lithium/metal sulfide 2	(10/5)	95.8	96.2
Lithium/metal sulfide 2	(10/10)	95.9	95.9
Lead acid	(7/5)	95.7	96.2
Lead acid	(7/10)	96.1	96.1
Zinc chloride	(5/5)	96.1	96.2
Zinc chloride	(5/10)	96.2	95.4
Sodium chloride	(7/5)	95.0	96.2
Sodium chloride	(7/10)	95.4	96.1

The ac megawatt-hour discharge capacity of the system can be increased by selective use of augmentation whenever the battery voltage exceeds the minimum dc voltage of 2200 V. In this mode, augmentation is employed when the battery voltage exceeds the minimum dc voltage of 2200 V. The converter is then maintained at 2200 V while the augments supplies the differential voltage required. This technique supplies supplemental energy from the augments for a greater duration of the charge cycle, thereby increasing the system capacity. However, when the augments is operated at less than full output voltage, there is a lagging var demand by the augments. This var demand can be supplied either by the utility line or by the converter. When supplied by the converter, a reduction in the converter's power capacity is required for this portion of the cycle to keep the system within its kVA rating of 1 pu. This relationship can be expressed as follows:

$$P = (1 - Q^2)^{1/2}$$

where

P = allowable real power in pu

Q = var demand of the augments in pu

The 7-hour/10-hour sodium chloride battery was evaluated with the use of selective augmentation. The results are presented in Table 3-10 and show that the cycle efficiencies are approximately the same. This reduces to 6 percent more discharge megawatt-hours, where the phase-controlled rectifier vars are supplied by the modified fuel cell converter.

TABLE 3-10. BATTERY SYSTEM PERFORMANCE WITH SELECTIVE AUGMENTATION

<u>Mode of Augmentation</u>	<u>Power-Conditioner Efficiency, %</u>	
	<u>Discharge</u>	<u>Charge</u>
Minimum use as required by profile	96.1	95.4
Selective augments, vars from utility	96.2	95.6
Selective augments, vars from converter	96.2	95.5

Notes

- 1) 1.6:1 voltage ratio augments
- 2) Sodium chloride 7-hour/10-hour cycle
- 3) Minimum use augmentation: augments used at maximum augmentation above 2860 Vdc
- 4) Selective augmentation: augments used above 2200 Vdc

TASK 2 - PRESENTATION OF CONVERTER TEST RESULTS

Test Program

The objective of the test program was to demonstrate the features of a self-commutated inverter-rectifier utilizing megawatt-scale hardware. The features successfully demonstrated were:

- o Operation at unity power factor for charge and discharge
- o Transition from charge to discharge with no dc polarity reversal
- o Control of leading and lagging vars during charge, discharge, or zero real power
- o Cancellation of lower-order harmonics
- o Operation through most ac system voltage disturbances
- o Operation in a trickle-charge mode

This met the objectives of the test plan.

The hardware utilized for the test was a converter referred to as the "0.5-MW Development System." It consisted of two 900-kW, three-phase inverter bridges, series reactors, harmonic-cancellation transformer, output transformer, and associated switchgear, logic, and controls. The system has been extensively tested in parallel with the utility line in the discharge mode with a 500-kW dc power supply as a source (3). With the exception of the inverter bridges, the system was rated at 500 kW to match the power supply. The major system modifications and additions for also operating as a rectifier were:

- Addition of 200-kW dc load bank in parallel with the 500-kW dc power supply
- Addition of a new control and digital meter display panel in the control console with required interface signals
- Control and protection logic modifications to allow rectifier operation with control of rate-of-change for transient tests
- Addition of control functions to allow remote operation
- Addition of instrumentation interfaces and instruments for measuring required steady-state and transient parameters

The test program consisted of an established procedure for line paralleling the system and then operation and data recording at preselected load points to demonstrate real (charge and discharge) and reactive (lead and lag) power control and transient excursions to demonstrate rapid transition from charge to discharge and vice versa. Additional data on harmonics was taken and part data on operation during utility line disturbances. In brief, the test procedure was as follows:

- Energize dc power supply, dc load bank, and input filter caps.
- Start converter isolated from utility and set initial phase/ magnitude condition.

- Close line paralleling breaker and place system in automatic operating mode.
- Set test points and record data to demonstrate self-commutated converter features.

Test Results

The tests that were performed and their results demonstrated the capabilities of a self-commutated converter for use in battery energy storage systems. The test results are discussed in detail on pages 5-8 through 5-10. Briefly, the results are:

- The system operated at 200 kW at unity power factor in both the charge and discharge modes.
- The system was transitioned from 200 kW charge to 200 kW discharge and vice versa in less than 0.5 seconds.
- The system was operated at unity power factor at the maximum charge and discharge levels, with leading and lagging vars at intermediate charge and discharge levels, and with leading and lagging vars at zero net real power.
- Spectrum analysis of the output transformer primary and secondary voltages for all operating conditions showed cancellation of the 5th, and 7th harmonics in the two-bridge 0.5-MW system. Additional data from a 1-MW three-bridge system showed cancellation of the 5th, 7th, 11th, and 13th harmonics.
- Previously, the 0.5-MW system had operated for 169 hours in line parallel without system interruption due to line disturbances. The 1-MW system in 1022 hours of line parallel operation had experienced 106 voltage impulses greater than 33 percent of nominal with no system interruptions.
- The system was operated in two trickle-charge modes, 90 kW and 5.3 kW, and data that were taken showed the dc current to be continuous.

Conclusions

- The demonstration of the principal operating features of a self-commutated converter validates the technical feasibility of this approach for the energy storage application which requires operation in both the inversion and rectification modes with the ability to transition successfully from one mode to the next.
- The tests, using United's 0.5-MW development system, modified for converter operation in conjunction with supplemental data from United's 1-MW pilot inverter, have demonstrated the following capabilities for a self-commutated converter:

The ability to operate at unity power factor without capacitors: operated at 200 kW, unity power factor in discharge mode (inversion) and at 200 kW, unity power factor in charge mode (rectification).

The ability to supply vars: operated at 180 kW, 0.9 PF, delivering vars, discharge and charge modes; 180 kW, 0.9 power factor, receiving vars, discharge and charge mode and 200 kvar, 0 PF, receiving and delivering vars.

The ability to convert from charge to discharge mode without a dc polarity change: switched from 200 kW charge to 200 kW discharge in less than one-half second.

Cancellation of low-order harmonics: 5th and 7th harmonics effectively canceled for all conditions, and 1-MW pilot inverter system canceled all harmonics, up to the 17th.

Ability to operate through ac system transients: 1-MW pilot inverter system operated through 1066 hours in parallel with utility line.

Trickle charge: the 0.5-MW self-commutated inverter-rectifier system has operated to 5 percent of the bridge rating without discontinuous dc current.

- The techniques employed to control and display real and reactive power in the charge and discharge modes demonstrate the elements of a remote dispatch application.
- The work under Task 2 - Test Self-Commutated converter features has been successfully completed.

TASK 3 - REQUIREMENTS FOR ISOLATED OPERATION

A survey of five utilities and three A&E firms was made to determine a preliminary specification for isolated operation for energy storage systems. The utilities surveyed were municipals or rural electric associations. Their small size, use of radial distribution systems, and purchase of power from outside sources, make them the most likely candidates for isolated operation. Previous studies indicated that large utilities with grid distribution networks did not require isolated operation because of the low probability of network outage.

The original plan was to survey eight utilities. However, the limited response of the first five organizations surveyed caused a change in plans. Three A&E firms that specialize in work for municipal/REA utilities were substituted for the last three utilities in an attempt to strengthen the technical requirements portion of the survey.

The visits to the first five utilities resulted in only one completed survey form. The lack of response to the survey form is attributed to the lack of a technical data base relating to this type of application from which a response could readily be formulated. Therefore, the conclusions are based upon comments made during the interviews and the one survey form.

Three of the five utility organizations were interested in battery storage systems for isolated operation, while all five expressed an interest in fuel cell systems. The only specific application identified by two utilities is a converter operating at the end of a long radial transmission line for emergency operation. The completed survey form indicates a requirement for an 18,000-kW capacity, available for 48 hours, for this type of application. This would be consistent with the use of two 9.2-MW converter modules; however, the long duration of the need makes this requirement appropriate to a fuel cell rather than a battery source.

All of the utilities and A&E firms surveyed agreed that it would be impossible to write a single specification to cover the isolated operation.

The response from A&E firms indicated concerns in the following areas:

- Fault-current capability
- Integration of substation controls and protective relaying
- Modification to substations and line protection for integration with the converter

Two A&E firms provided data packages with useful information on typical systems characteristics and fault currents for REA and municipal systems.

One of the A&E firms performed a limited analysis of the general application of battery systems and fuel cells or combustion turbine generation for peaking application for a municipal system. The analysis concluded that batteries and fuel cells or combustion turbine generation may have application for peaking service, but no conclusions were drawn with respect to the requirements for isolated operation.

The results of the survey are inconclusive with respect to the long-term requirements for isolated operation of energy storage systems because of the limited response. The limited response to the questionnaire also precluded preparation of the desired specification.

SECTION 4

TASK 1 – SELECT MODIFICATION OF FCG-1 INVERTER

SECTION 4. DISCUSSION OF TASK 1 - SELECT MODIFICATION OF FCG-1 INVERTER

INTRODUCTION

This section describes the results of United's work leading to the conclusion of Task 1 - Select Modification of FCG-1 Inverter.

Task Objectives

The present 27.6-MW FCG-1 inverter system is designed for fuel cell operation in the inverter mode only. This design can be modified to operate as a two-way converter for both charging and discharging storage batteries. The objective of this task is to select the most attractive modifications of the fuel cell inverter for converter operation and to provide a preliminary estimate of its characteristics. This task is broken down into the following elements:

- Define electrical interface requirements for converters at battery and utility bus.
- Expand present models of the inverter system to represent converter operation.
- Select one of the following options based on performance review.
 - 1) If performance is acceptable, prepare a conceptual design description of the FCG-1 modified for use as a converter.
 - 2) If performance is not acceptable, evaluate changes to the basic system configuration.
- Evaluate selected option.

PRINCIPLES OF OPERATION OF SELF-COMMUTATED CONVERTER SYSTEMS

Description of Baseline Self-Commutated Converter

Figure 4-1 shows a converter system module derived from United's 27.6-MW utility inverter system. Each converter system module, which is nominally rated at 9.2 MW ac, is fed from a source of unregulated dc energy (battery or fuel cell).

Figure 4-1. Converter Rectifier System Module

In the converter module, three self-commutated converter bridges convert the input dc into three three-phase, quasi-squarewave voltages that are phase-displaced. These voltages are fed to series reactors that function as an isolating impedance between the converter and utility line for control purposes. From the series reactors, the voltages are fed to the harmonic-cancellation transformer, which removes harmonics (up to the 17th) from the quasi-square-wave voltages. The voltages from the harmonic-cancellation transformer are combined and stepped up to the utility line level by means of a nearly stan-

dard utility transformer. Harmonics are further reduced, if necessary, by additional filters on the utility side of the transformer. Fuses and ac and dc switchgear are provided, as appropriate, for isolation and protection.

Parallel Operation with Utility Line

A simplified representation of a self-commutated converter system, operating in parallel with a utility line, is shown in Figure 4-2. An equivalent circuit version is shown in Figure 4-3.

Figure 4-2. Self-Commutated Converter System

Figure 4-3. Equivalent Circuit for Self-Commutated Converter in Parallel with Utility Line

By the use of an approach similar to that for analyzing generators in parallel with utility lines, the relationships for real and reactive power transfer may be derived as follows in vector notation:

$$E_1 = KE_{dc}$$

where E_{dc} = source voltage in per unit

K = function of converter voltage control

E_1 = 60-Hz component of quasi-squarewave voltage
generated in bridge in per unit

and

$$E_2 = E_1 - I(R_1 + jX_L)$$

where R_1 = series resistance in per unit

X_L = 60-Hz series inductive reactance in per unit

I = pole 60-Hz output fundamental current in per unit

E_2 = 60-Hz fundamental component of substation bus voltage
in per unit

If the resistance is assumed to be negligible and this equation is solved for transferred kVA:

$$\text{Transferred kVA} = P + jQ = \frac{E_1 E_2 \sin \delta}{X_L} + j \frac{E_2 (E_1 \cos \delta - E_2)}{X_L}$$

and P = real power (kw) in per unit

Q = reactive power (kvar) in unit

(positive P or Q indicates delivered to utility line)

δ = phase angle by which the bridge 60-Hz voltage component leads the utility line voltage.

From this equation, it can be seen that real power (P) transfer is represented by the first term and is proportional to the phase angle (δ) between the line and the bridge fundamental voltage. Reactive power (Q) is represented by the second term and is proportional to the difference between the 60-Hz component of the bridge voltage and the utility line voltage ($E_1 - E_2$). Thus, to a first approximation:

- the phase angle difference is regulated to control real power, and
- the dc source voltage is matched to the utility line by the converter bridge voltage regulator and controls reactive power.

Figure 4-4 shows the vector relationship of the self-commutated converter system voltages described by the equations. The solid lines are a vector set for a positive δ , and the dashed lines are a vector set for a negative δ . In the example shown, the utility bus voltage (E_2) is equal in magnitude to the fundamental voltage (E_1). Any difference between these two voltages, V_L , appears across the inductor L . Because V_L is assumed to be totally inductive, the current (I_L) into the utility line is shown lagging V_L by 90 degrees. For the positive δ example, the bridge is delivering power to the utility lines and the dc source driving the inverter-rectifier is discharging. If δ is negative, the current, I_L , is essentially 180 degrees out of phase with the voltages (E_1 and E_2) and the dc source driving the inverter-rectifier is accepting power (charging). In both cases the utility is supplying a portion of the vars consumed by the series L . The effective power factor angle, Θ , of Figure 4-4

can be modified by changing the relative magnitude of E_1 to E_2 . Figure 4-5 shows a power factor of unity compared to that shown in Figure 4-4. This was achieved by increasing the pole voltage E_1 with respect to E_2 . Alternatively, the power factor angle could be increased and vars could be either delivered or consumed if the E_1 -to- E_2 magnitude relationship is suitably modified.

In a practical case, the resistance of the system is not zero and the current I_L lags V_L by less than 90 degrees. Figure 4-6 is a power transfer map depicting the loci of constant real (P) and reactive (Q) power points versus phase angle and voltage ratio. The map illustrates the interaction of real and reactive power transfer for practical values of resistance. If the resistance were zero, the loci would be perpendicular to each other and parallel to the major axes of the chart.

Figure 4-4. Effect of Relative Phase Angle

Figure 4-5. Effect of Relative Voltage Magnitude

Figure 4-6. Power Transfer Map

Real and Reactive Power Control

Real and reactive power control during discharge (inversion mode) and charge (rectification mode) were shown to be functions of the inverter bridge fundamental output voltage magnitude and phase angle with respect to that of the utility. This section discusses the internal power flow and control in the self-commutated bridge. To simplify these discussions, the series resistance is assumed to be negligible and the bridge output voltage harmonics are not considered.

Real Power Control . Figure 4-7A shows a simplified single powerpole portion of the three-phase bridge introduced in Figure 4-2. To illustrate real power control, the fundamental pole voltage (E_1) is set equal to the utility line voltage (E_2), making the reactive power transfer zero, if we assume L to be a very small but finite inductance.

Figure 4-7. Real Power Control, Self-Commutated Single Power Pole

Thyristor Q_1 is gated on during the period T_1 , while thyristor Q_2 is gated on during the period T_2 . During their respective gating periods, each thyristor will conduct if its anode is positive with respect to its cathode.

In Figure 4-7B, at δ degrees ahead of $t = 0$, the thyristor Q_2 is commutated off by an auxiliary circuit (not shown), and a gate signal is applied to thyristor Q_1 . This causes point A of the pole to be switched from $-E_B$ to $+E_B$ and represents the point where the fundamental pole voltage waveform (E_1) crosses zero. The load current (i) has been flowing into the pole and cannot instantaneously change direction because of the inductance L . The current is now carried by diode D_1 . The voltage across D_1 will maintain Q_1 reverse biased. However, δ electrical degrees later, when the current is forced to zero by the voltage difference ($E_B/2 - E_2$), Q_1 will conduct and the load current (i) will build up in the positive direction.

At the end of the period T_1 (180 electrical degrees), the thyristor Q_1 is commutated off and a gate signal is applied to Q_2 . This action connects point A to $-E_B$. Again, the current continues to flow into the utility line because of the inductor L , but its path switches from Q_1 to D_2 . As in period T_1 , Q_2 will conduct δ degrees later (when the current goes to zero) and is forced in the opposite direction by ($-E_B/2 - E_2$).

At the end of period T_2 , the cycle repeats. The cycle previously described used a positive angle δ , such that the inverter current (i) is in phase with the utility voltage E_2 and power is being delivered in the inverter mode. In Figure 4-7B waveform, the current carried by the diodes (D_1 and D_2) is shown as a solid area, while the current carried by the thyristors (Q_1 and Q_2) is shown cross-hatched with the related conducting device indicated below. A comparison of these areas shows that the thyristors carry most of the current in the inverter mode.

Figure 4-7C shows operation using a negative δ angle. With the same reasoning applied as for Figure 4-7B, it can be seen that the utility is supplying power to the pole, since the current is 180 degrees out of phase with the utility voltage E_2 and operation is in the rectification mode. A similar comparison of relative current conduction areas (shaded vs. crosshatch) shows that the diodes carry most of the current in the rectification mode.

Reactive Power Control. Figure 4-8 is similar to Figure 4-7, except that it illustrates reactive power control. The relative phase angle δ is equal to zero, so that the real power transfer is equal to zero. In Figure 4-8B, E_1 is greater than E_2 and thyristor Q_1 is gated on during T_1 and Q_2 is gated on during T_2 . At time zero, the midpoint (A) of the pole is connected to $+E_B$, and the current (i) is being carried by D_1 . The current continues to flow through D_1 until the potential difference ($E_B/2 - E_2$) causes it to go to zero. Halfway through time T_1 , the current (i) goes to zero and thyristor Q_1 conducts. At the end of period T_1 , Q_1 is commutated off and the gate signal is applied to Q_2 . The inductor causes the current to continue to flow in the same direction and the path switches from Q_1 to D_2 . Halfway through time T_2 , the current (i) passes through the zero point and switches from D_2 to Q_2 . At the end of time T_2 , Q_2 is commutated off and the cycle repeats.

The cycle with E_1 greater than E_2 results in a current circulating between the dc source and the utility line. Since the current lags E_1 by 90 degrees, the converter bridge is operating at a lagging power factor and leading vars are being delivered to the utility. (This is similar to a generator supplying a motor load.)

Figure 4-8C shows the case where E_2 is greater than E_1 . With the same reasoning as applied to the action of Figure 4-8B, it can be shown that the current is leading the converter bridge voltage by 90 degrees, and the converter is receiving vars from the utility. Examination of the shaded areas under the current (i) curve in Figure 4-8B and C shows that the average currents carried by the diodes and thyristors are equal for this reactive power case.

Figure 4-8. Reactive Power Control, Self-Commutated Single Power Pole

FCG-1 FUEL CELL INVERTER SYSTEM

Baseline Technology

A description of the FCG-1 fuel cell inverter system which is the basis unit from which the 4.8-MW unit was derived is included to define the baseline technology. The 27.6-MW FCG-1 fuel cell inverter system consists of three 9.2-MW modules. The 9.2-MW module basic building block is described in the following sections to establish the foundation for the work performed in this task. The major components of the FCG-1 fuel cell inverter system are listed in Table 4-1.

TABLE 4-1. MAJOR COMPONENTS OF THE INVERTER

Component	*Pallet Location
Three inverter bridges	F
Inverter logic and controls	F
Preload	F
DC power supply	F
Three series reactors	G
One phase-shifting transformer	G
One summing transformer	G
AC breaker	G
Output transformer	Separate
DC protection	Separate
*Elements of fuel cell power plant	

Physical Description

The inverter system components are factory assembled within a weather enclosure that is configured as two truck-transportable pallets (F and G) which together with a number of additional pallets make up the basic 9.2-MW module of a fuel cell power plant. These pallets are shipped individually and connected together at the site. The assembled inverter system, shown in Figure 4-9, has provisions for heating, cooling, and ventilation. The output transformer is mounted separately, adjacent to the enclosure. The dc breaker is located adjacent to the fuel cell module but is considered a part of the complete power-conditioning subsystem. Arrangement of the power-conditioning system is shown in Figure 4-10, and described as follows:

- The dc power supply, located on Pallet F, is completely self-contained in a single indoor enclosure, prewired and complete with necessary controls, buswork, and input/output connections.

(WCN-5542)

Figure 4-9. Power-Conditioner Assembled Enclosure

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Figure 4-10. Arrangement of Inverter Power-Conditioner System Components

- The preload is self-contained in a separate indoor enclosure, located within the inverter system weatherproof enclosure on pallet F, pre-wired and complete with necessary buswork, lugs, connectors, etc. for power and control input/output connections. The preload is not required for battery applications.
- There are three inverter bridges. Each bridge is forced-air cooled and packaged in its own frame with acoustical enclosure, as shown in Figure 4-11. The inverter bridges are located on pallet F. Each bridge is made up of the following:
 - 1) Three series power thyristors and snubber circuits per switch (18 total devices per bridge)
 - 2) Two series commutation thyristors and snubber circuits per switch (12 total devices per bridge)
 - 3) Three series main diodes and snubber circuits per switch (18 total per bridge)
 - 4) Three sets of commutation capacitors (30 total per bridge)
 - 5) Commutation inductors (3 total sets per bridge)
 - 6) Input filter capacitors (12 total per bridge)
- Phase-shifting and summing transformers are class A/FA transformers located on pallet G.
- Each of the three series reactor assemblies is in a separate metal accoustical enclosure and is A/FA class.
- The OA/FA class output transformer, on pallet H, is shipped separately and located adjacent to pallet G.
- The ac breaker is located on pallet G. It is in a separate metal enclosure and has its own controls and protection.

Figure 4-11. Inverter Bridge Assembly

(WCN-5385)

Functional Description

The inverter system in the FCG-1 power plant converts dc power from the fuel cell dc module to three-phase, 60-Hz ac power at 13.8 kilovolts. An inverter system functional block diagram is shown in Figure 4-12. It includes a dc breaker, dc power supply, preload, inverter bridges, series reactors, phase shifting and summing transformers for harmonic reduction, an output transformer, and an ac breaker.

Figure 4-12. Inverter System Functional Block Diagram

In the inverter system, the unregulated fuel cell dc output voltage is fed to three self-commutated inverter bridges that convert it into a three-phase, ac-modulated quasi-squarewave voltage. The outputs of the inverter bridges are fed through series reactors into the harmonic-cancelling transformer. The bridges are operated in time relationship to each other to permit cancellation of output voltage harmonics up to the 17th harmonic. Remaining harmonics are filtered, if required, to meet the specification.

The outputs of the harmonic-cancelling transformers are combined and stepped up to the voltage level of the utility line by means of an output transformer. Series reactors are connected between the inverter bridges and the phase-shifting transformers to provide an inductive impedance to the utility line for control purposes. Appropriate ac and dc switchgear and fuses are provided for isolation and fault protection.

The following is a functional description of each of the major subsystems in the inverter system.

DC Protection Subsystem - The advanced technology dc protection subsystem provides automatic current-limiting interruption of the dc line between the fuel cells in the dc module and the inverter system in the event of a fault. This is accomplished by means of separate interrupting devices on the positive and negative line. When the devices interrupt the normal current path, the fault current is transferred into a special high-voltage fuse, which then interrupts the arc. This dc breaker device has three types of current sensing and control: maximum current, rate of current rise, and an inverse time current characteristic. The dc breaker system also includes a motor-operated mechanical isolation switch for no-load disconnect during startup/shutdown and maintenance or checkout.

DC Power Supply - The dc power supply has several functions. On startup, it is used to charge the inverter input filter capacitors prior to bridge startup and application of load. It provides dc power to the inverter system for diagnostics. It also provides a means of activating the inverter system during

use in an independant var control mode when the dc module is inactive. The dc power supply is controlled by the logic.

Preload - The preload is a switched transient-rated load bank that is used to limit the dc voltage on the dc input side of the inverter system during startup and shutdown transients when the inverter system is not providing output power. In addition to the resistors and switch, the preload includes high frequency filter capacitors, dc current sensors, and voltage sensors and is controlled by the inverter system logic.

Inverter Bridge Assembly - The inverter bridge assembly converts the unregulated dc voltage from the fuel cells (dc module) into a three-phase, ac-modulated, stepped-wave ac voltage. The inverter bridge (Figure 4-13) is made up of the following major components:

- Power thyristors
- Commutation thyristors
- Main diodes
- Commutation capacitors
- Commutation inductors
- Input filter capacitors

Harmonic-Cancelling Transformers - The converter output voltage waveform contains only odd order, non-triplen harmonics, since on a three-phase line-to-line basis the triplen frequencies (odd multiples of the third harmonic) do not appear. Therefore, a means of preventing the remaining odd non-triplen harmonics through the 13th from appearing at the converter output is required to produce a low distortion voltage waveform. The technique employed in the converter system is the use of a harmonic transformer assembly, which consists of two low-kVA, convection-cooled A/FA, dry type transformers. Both transformers are constructed with standard utility type transformer laminations and foil windings. Each transformer is mechanically braced to withstand fault currents from an infinite bus through the output transformer's percent impedance.

Figure 4-13. Simplified Schematic of Three-Phase Inverter Bridge

As previously mentioned, these transformers are designed to be convection cooled, but forced-air cooling is employed above 60% load to improve system efficiency.

Figure 4-14, shows the voltage and phase relationships at the output of the bridges, the phase shifting, and summing transformers and at the output transformer input.

Figure 4-14. Harmonic Cancellation

Series Reactors - There are three series reactor assemblies. Each assembly has three class AFA air-core inductors. These inductors provide 16 percent of the impedance between the inverter output and the utility line. This impedance, together with an additional 1 percent impedance in the phase-shifting transformer and summing transformer and another 5 percent impedance in the output transformer, provides a total of 22 percent impedance to limit surges and provide for the stable control of real and reactive output power.

Output Transformer - The output transformer, which boosts the power plant output to utility line voltage, is a three-phase, 60-Hz, oil-filled, forced-air cooled, pad-mounted transformer. It is 110-kV BIL design, class OA/FA rated 10,000 kVA, 13,800 volts high side, and 2000 volts low side. The transformer consists of four windings: a wye-connected high-side winding and three low-side delta windings. The transformer includes an external, manually

operated, no-load tap changer for high-voltage taps to permit $\pm 2\frac{1}{2}$ percent and ± 5 percent adjustment of high-side rated voltage.

AC Breaker - The ac breaker is a 13.8-kV, metalclad, draw-out air circuit breaker with controls and protection.

Control Logic And Diagnostic Assembly - The control logic and diagnostic assembly, located on pallet F, consists of two free-standing cabinets containing power supplies, printed circuit logic cards, relay rack, transformer rack, internal wiring, input/output connector interfaces, etc. The control logic section provides the necessary control for the Demonstrator power conditioning subsystem. The diagnostic section provides diagnostic, recording equipment, and local control capability.

AC Disconnect - An ac utility grounding, fused manual disconnect switch is provided by the utility at the output between pallet G and the utility line. This switch provides isolation from the distribution system.

INTERFACE REQUIREMENTS FOR BATTERY OPERATION

The interface requirements are separated into three basic parts:

- General considerations
- Electrical considerations
- Protection and protection coordination

General considerations include such things as environmental, maintenance, and safety features. Electrical considerations include both dc and ac interfaces and operating requirements. Protection and protection coordination are concerned with the coordination of the dc source, the power conditioner, and the ac system protection means. Because the general and protection considerations are fundamentally the same as in United's FCG-1 electric utility program, the FCG-1 background is applied in those areas. Similarly, the ac portion of the

electrical interface requirements is based upon the FCG-1 foundation. The dc portion of the electrical interface requirements is based upon FCG-1, insofar as a fuel cell is concerned; but for batteries, the survey described in the following subsections provided the required definition of the dc source.

The interface requirements are summarized in Table 4-2 and given in Appendix A1. Several important areas of consideration (power rating base, dc voltage range, power rating, and harmonics) are discussed in the following paragraphs.

TABLE 4-2. BATTERY POWER CONDITIONER INTERFACE REQUIREMENTS

<u>Item</u>	<u>Characteristics</u>
Rated ac power	27.6 MW at unity PF
Load range	25 to 100%
DC voltage	
Minimum voltage	2200 volts
Maximum voltage ratio during discharge	1:3 to 1
Maximum voltage ratio during charge	1:7 to 1
Average full load efficiency	95% minimum
Frequency	60 Hz
AC voltage	13.8 kV
AC voltage range	+5 to -5% (normal) +10 to -20% (emergency)
Rated maximum ac fault current	110%
Power factor	Unity, lag, or lead within kVA capability
Total harmonic voltage	4% of fundamental
Unbalance, L-L voltage	2%
Recovery after fault	10 cycles

A dilemma exists in selecting a base because the power rating of the system is a variable, depending both on the point of operation in a battery charge/discharge cycle and on the relative duration of the charge and discharge times. The reason for the variable power rating is that the battery efficiency and average converter power rating change as the relative time durations change. Depending upon the chosen operating point, the equipment cost in dollars per kilowatt can change even though the total capital expense does not change.

The self-commutated converters output capability is limited by different components during different portions of the battery cycle. Overall, the ac output transformer limits the power on a steady state basis to its rated value. For the discharge portion, the output power is limited by the commutating capability of the bridge. Although this capability increases with increasing input voltage, it cannot be utilized without increasing the transformer size. During var operation and charge operation, the diodes in the self-commutated bridge are the major limiting factor.

In this study, the use of the FCG-1 converter for battery storage applications is examined. Since the use of a specific design is being considered for use with a multitude of batteries, United has chosen to maximize the power capability of the existing design over the proposed operating range. Accordingly, the power conditioning system is rated to deliver rated power over the entire discharge voltage range and charge voltage range.

For fuel cells, the dc voltage range is obtained from the FCG-1 program. The 2200-vdc minimum voltage is consistent with United's fuel cell program and with the desire to provide a preliminary design suitable for both battery and fuel cell operation. For batteries, the studies of advanced battery cell characteristics provided the definition.

The nominal converter system rating of 27.6-MW ac, consisting of three 9.2-MW ac modules, is derived from the FCG-1 fuel cell inverter system rating. Consideration will be given to modification of this criterion if advantageous.

The limits for harmonic voltages introduced into the utility ac network are based on a proposed "Guide for Harmonic Control and Reactive Compensation of Static Power Converters" as prepared by the IEEE-IAS Subcommittee on Harmonic Control and Reactive Compensation. Studies currently in progress under EPRI Research Project 1024-1, "Study of Distribution System Surge and Harmonic Characteristics," will provide further definition of these limits. The Power Systems Division of United Technologies is participating in this project under subcontract to McGraw Edison Company.

RESULTS OF ADVANCED BATTERY MANUFACTURERS SURVEY

A battery manufacturers survey form was generated to acquire the battery characteristic information necessary to define the battery/inverter-rectifier interface. This document, which is presented in Appendix A2, was forwarded by DOE and EPRI to six advanced battery developers. The survey form was designed to provide information pertaining to the power levels and voltage ranges during charge and discharge, battery performance characteristics for 3-, 5-, and 10-hour discharges, available fault current, and the effects of aging. Survey returns received from the battery developers were followed up by telephone conversations in cases where additional information was required.

To gain further technical data on advanced energy storage batteries, visits were made to Bechtel, EPRI, and Argonne National Labs. In addition, United representatives participated in the First Annual ERDA Battery Contractors Coordination Meeting January 27-28, 1977, and BEST facility Workshop II February 10, 1977, and the Lead Acid Battery Workshop December 9-10, 1976. Information was obtained from these sources on the following types of energy storage batteries:

1. Sodium-sulfur (two developers)
2. Sodium-antimony trichloride (sodium chloride)
3. Zinc-chlorine
4. Lithium/metal sulfide (two developers)
5. Lead-acid

The specific battery information derived from the above sources is summarized in Appendix A3. The discussions with the advanced battery manufacturers and investigations under this contract indicate that additional consideration must be given to the dc source interface requirements during startup, standby, and shutdown, and special requirements such as equalizing charge and trickle charge in future work on power conditioning systems. Data on the effect of aging on battery characteristics was also unavailable and is required. The battery characteristics can be divided into two major categories, as defined by the charge and discharge periods. The first category is where the charge time is less than or equal to the discharge time, which yields a system that is charge-limited. Although the survey revealed some variations, the typical cycle times for charge-limited systems are a 7-hour charge and a 10-hour discharge. The second category is where the charge time is greater than the discharge time, which yields a system that is discharge-limited. The typical cycle times for a discharge-limited system are a 7-hour charge and a 5-hour discharge. The battery voltage characteristics for the 7-hour charge and 10-hour discharge cycle can be summarized as follows:

- A. A maximum voltage ratio for end-of-charge to end-of-discharge of 1.6:1 satisfies all batteries surveyed except for the lithium/metal sulfide type 1, which has a voltage ratio of 2.06:1.
- B. A maximum voltage ratio for start-of-discharge to end-of-discharge of 1.30:1 satisfies all batteries surveyed except of lithium/metal sulfide type 1, which has a ratio of 1.7:1 and sodium chloride, which has a ratio of 1.35:1. The 1.35:1 voltage ratio of the sodium chloride battery was reduced to 1.30:1 with a negligible effect on the available energy during discharge.

The battery voltage characteristics for the 7-hour charge and 5-hour discharge cycle can be summarized as follow:

- A. A maximum voltage ratio of end-of-charge to end-of-discharge of 1.7:1 satisfies all the batteries surveyed except for the lithium/metal sulfide Type 1, which has a ratio of 2.4:1.
- B. A maximum voltage ratio for start-of-discharge to end-of-discharge of 1.3:1 satisfies all the batteries surveyed except for the lithium/metal sulfide type 1, which has a ratio of 1.8:1.

The battery voltage characteristics for the 7-hour charge and 3-hour discharge cycle can be summarized as follows:

- A. A maximum voltage ratio for end-of-charge to end-of-discharge of 1.9:1 satisfies all the batteries surveyed except the lithium/metal sulfide type 1, which has a ratio of 2.8:1.
- B. A maximum voltage ratio for start-of-discharge to end-of-discharge of 1.5:1 satisfies all the batteries surveyed except for the lithium/metal sulfide type 1, which has an estimated ratio of 1.7:1.

Generation of Battery System Curves

To perform a cycle performance analysis, the battery data must be expressed as a voltage and current profile as a function of time for a complete cycle of both charge and discharge. In some cases, the data received from the battery developers required translation to obtain the desired profile. The translations included consolidating charge/discharge data and interpreting polarization curve data and ampere-hour capacity curve data. The information received from the battery developers was on a per-cell basis. To be useful in a power-conditioning system, a battery matrix of multiple series/parallel cell configuration must be defined to match the capabilities of the conversion equipment employed. For this program, a flexible cell matrix was assumed for each specific battery evaluated. The system voltage schedule was developed, based on a minimum system voltage of 2200 Vdc, which is the same as the fuel cell system. The minimum voltage point occurred at the end-of-discharge point in all cases.

This procedure defined the number of cells required in series by dividing 2200 volts by the per-cell voltage at this point. Once this minimum system voltage point (2200 Vdc) had been established, the balance of the voltage schedule was ratioed to reflect that particular battery's characteristics by multiplying the number of cells used in series by the per-cell voltage at each point in time during the cycle.

To develop the current profile, the maximum current point per cell for each battery was determined from the survey response. For the particular battery under consideration, the maximum dc power capability of the power conditioning system was evaluated at this point to establish the maximum system dc current required. The number of cells to be used in parallel was then determined by dividing this system dc current by the capacity of each cell. Once this maximum system current point had been defined, the balance of the current schedule was ratioed to reflect that particular battery's characteristics by multiplying the number of cells used in parallel times the per-cell current at each point in time during the cycle.

This procedure led to the development of each battery system voltage and current profile as a function of time during the charge and discharge cycles. A representative curve that depicts the 7-hour charge, 5-hour discharge cycle for the sodium chloride battery is shown in Figure 4-15. The system profile curves were also developed in per-unit values to aid in interpreting ratios between various portions of the cycle. A copy of the actual and per unit voltage and current profile curves as developed for each type of battery evaluated is given in Appendix A4.

HYBRID MODEL

A basic evaluation tool used in this study was the EAI hybrid simulator. As part of the work under this contract, the existing baseline fuel cell inverter simulation model was modified for converter operation. The hybrid computer simulations were used to establish design requirements for system components.

Figure 4-15. System Profile Curve for Sodium Chloride Battery

Description of Basic Model

An analytical system model of the self-commutated power conditioner was developed and is in operation on an Electronic Associates, Inc. Pacer 600 Hybrid Simulator. The elements in the equivalent circuit diagram were described by a set of ordinary differential and algebraic equations, with appropriate discontinuities to account for switched conducting paths. The analog portion of the hybrid computer solves these equations with parallel computational components. The parallel logic capability of the analog computer is used to perform required discontinuous switching and for control. The digital computer portion of the

hybrid computer is used for overall control and to perform complex mathematical computations on waveforms generated in the analog computer. A Hytran Operations Interpreter (HOI) program, which is used for preparation, setup, and checkout of the simulator, was used to establish the operating conditions and parameters for the system under study. The Real Time Operating System (RTOS) was employed to permit background digital computation during the idle time not required by the hybrid simulation.

The Pacer 600 Hybrid Computer consisted of two 681 Analog computers, each having 120 digitally set coefficient units and approximately 150 computing elements. These were interfaced to the Pacer 100 Digital Computer with a high-speed data interface consisting of a 24-channel, 125-kHz analog-to-digital converter and 48 digital-to-analog converter channels.

The digital computer (Pacer 100) consists of a 64 k of 16-bit memory operating in a foreground/background user environment with a card reader, a line printer, two disc drives, four magnetic tapes, two CRT terminals, and a floating-point hardware processor. A diagram of the system is shown in Figure 4-16. The fuel cell provides dc power to three inverter bridges operating in a phased sequence whose outputs are fed through harmonic-cancellation transformers and series reactors into an output transformer.

The inverter bridge commutation circuits are simulated in detail to provide data for design and operational performance evaluation of the self-commutated system. To simplify computer requirements, only one of the three inverter bridges is simulated in detail. The output waveform from the bridge is fed into a digital transport delay program, which provides the waveforms for the bridges that were not simulated. This method of representation is suitable since the other two inverter bridges are operating similar to the first bridge except for a phase shift between the outputs of the bridges during normal operation.

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Figure 4-16. EAI Hybrid Simulator Model Diagram

The outputs of the three inverter bridges pass through series reactors and are combined in a set of harmonic-cancellation transformers so that the first harmonic that appears is the 17th harmonic of the 60 Hertz fundamental. The output voltages of these cancellation transformers are then coupled into a three-phase output transformer. The output of this three-phase transformer is coupled through a transmission line to the power utility system. In addition, a local load appears across the output transformer, and there is a high-pass filter that can be switched into the simulation, if necessary, to reduce harmonics that are not cancelled by the harmonic-reduction transformers.

The control scheme implemented on the self-commutated converter permits simulated operation of the model over the same wide load and power factor range as the actual full-scale fuel cell hardware. The digital computer has been programmed to sample and store waveshapes from the analog program. A Fourier analysis routine, incorporated in the digital program, is used to generate the harmonic spectrum of any of these waveforms. Numerical information regarding the value of each waveform, its fundamental component, and total harmonic distortion, as well as display of the magnitude of each harmonic

signal, is available to the user on the CRT and in hard copy. Calibration and verification of the simulation was accomplished by comparing the results of the simulated system with data taken from Power Systems Division's 15-kW model system and the 1-MW fuel cell generating system. A high degree of correlation was obtained between waveforms and quantitative measurements of the performance of the system.

Model Modifications to Operate as Converter

A number of changes to both the software and hardware of the hybrid computer simulator were required to operate and evaluate the fuel cell inverter system as a battery-driven converter system.

The Hytran Operations Interpreter (HOI) program was modified to include a representation of the battery dc source (Figure 4-17) as well as to maintain the fuel cell model in the machine.

Figure 4-17. Battery Source Model

The computer operational limits were extended to allow full four-quadrant operation. Regulated power reversal (rectifying) for battery charging was correlated to the expanded power transfer contour map shown in Figure 4-18. This map is a locus of lines representing operation at constant vars, either leading or lagging, and operation at constant power, either inverting or rectifying.

The analog patch panels were revised also to include the selection of either battery or fuel cell model and to add the digitally-controlled attenuator representing the battery voltage and its internal series impedance.

Figure 4-18. Per Unit Power Map

PERFORMANCE OF FCG-1 INVERTER SYSTEM AS CONVERTER

Evaluation with Hybrid Simulator

Using the interface requirements defined from the storage battery survey responses and presented in the previous section, the inverter system of Figure 4-19 was evaluated as a converter. The baseline voltage and current profile for the initial evaluation was the 7-hour charge/10-hour discharge cycle shown in Figure 4-20. The overall dc voltage range is 1.6 to 1 from end-of-charge to end-of-discharge. Therefore, for an end-of-discharge system voltage of 2200 Vdc (minimum operating voltage of fuel cell inverter), the maximum operating voltage is 3520 Vdc. The dc voltage range from start-of-discharge to end-of-discharge is 1.3:1, which yields a maximum voltage of 2860 Vdc during the discharge cycle.

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Figure 4-19. FCG-1 Converter System Module

Figure 4-20. Baseline Battery Cell Profile

The hybrid simulator was operated as a converter, and voltage and current waveforms were obtained for components such as bridge diodes, thyristors, input filter, series reactor, harmonic-cancellation transformer, and output transformer. Figures 4-21, 4-22, 4-23 and 4-24 are representative of the converter application data obtained with the model.

Figure 4-21. Bridge Diode Current, Rectification

Figure 4-22. Bridge Thyristor Current, Rectification

Figure 4-23. Harmonic Cancellation TR Transformer Winding Voltage, Rectification

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Figure 4-24. Series Reactor Voltage, Rectification

These data were taken with the simulator for the conditions of:

- Rectification mode at end-of-charge voltage
- Unity power factor
- Balanced line conditions

Figure 4-21 shows the bridge rectifier current. The pulses, located at approximately 120, 250, and 340 degrees, are the results of commutation current, while the partial sinusoid is a portion of the pole output current. The Figure 4-21 waveform illustrates the requirement for the diodes to handle increased currents in the rectifier mode. Figure 4-22 shows the current through the main thyristor, which is connected anti-parallel to the bridge rectifier. As in the rectifier, the pulses result from the commutation current and the sinusoidal segments are the thyristor's share of the pole output current. Since operation is in the rectifier mode, the main thyristor currents are small.

Figure 4-23 shows the waveform appearing on a winding segment of one harmonic-cancellation transformer. The waveform contains a finite fundamental voltage component produced largely by the phase relationship of the inverter pole to the utility voltage and to the lower bridge. The stepped waveform results from harmonic cancellation of a portion of the pulse-width-modulated voltages generated by the inverter pole.

Figure 4-24 shows the waveform appearing on the series reactor. The fundamental component is produced by the pole output current. The sharp spikes represent voltage drops from the high-frequency components of the pulse-width-modulated voltages generated by the inverter pole.

Voltage Safety Factor

Each half of the baseline powerpole has three thyristors in series to perform the main switching function. The voltage stress on these series thyristors is a summation of a steady state and a transient component. The steady state

component is equal to the dc input voltage being blocked. The second component is a short duration transient caused by the commutation of the alternate series thyristors. The greatest stress occurs with the simultaneous application of the extreme of both components.

The worst case steady state stress on the converter bridge occurs when the input voltage is at the operating maximum of 2860 volts across the bridge.

The transient voltage is a function of the circuit design parameters and the maximum commutation capacitor voltage. The design of the voltage forcing circuits and the arrangement of the commutation inductors are the principal circuit parameters involved. The design of these circuits requires a trade-off between voltage margin and efficiency. The commutation capacitor voltage is modulated in proportion to the load current, and its maximum voltage occurs at peak surge current.

The worst case transient condition occurs after the commutation of the maximum permissible surge current. This surge current is induced by a lightning or large switching transient on the utility line. Upon completion of the commutation of the main thyristors carrying the surge current, the commutation capacitor voltage reaches its maximum value. These main thyristors are then subject to the maximum voltage transient when the main thyristors in the other half of the powerpoles are commutated off.

Voltage safety margins for series thyristors must be established for the worst case in the entire string and not for the string total. In the base line design, three 1800-volt thyristors must block 2860 volts on a continuous basis. Therefore, the worst case device must block $1/3$ of 2860 volts plus the unbalance caused by dissimilarity between thyristor characteristics. Matching of device characteristics by the manufacturer and the voltage forcing network keep this voltage unbalance within 100 volts. Steady state and device characteristics impose a maximum of 1050 volts on a thyristor.

The transient voltage imposed is calculated to be 340 volts per thyristor. The total worst case voltage stress on a thyristor is $1050+340$ or 1390 volts.

The proposed thyristors have an 1800 repetitive voltage rating and a 1900 volt non-repetitive rating. As the commutation of maximum current is predicted to be an occasional occurrence, the non-repetitive rating is applicable. Thus the devices have a margin of $1900 - 1390$ or 510 volts under the worst case conditions. This amounts to a margin of 35 percent.

In summary, the voltage margins for the baseline design main thyristors are established based upon a worst case combination of a steady state and transient voltage stress occurring simultaneously. The transient stress level is a function of circuit design parameters and is adjusted to provide adequate voltage margin while maintaining high efficiency. The baseline design has a voltage margin of 35 percent as compared to the 15 percent minimum value considered adequate.

Required Component Changes

The analysis of the FCG-1 inverter modified for a 1.6 to 1 voltage range of converter operation leads to the following component change requirements. The input filter capacitor maximum voltage would be increased from 2860 to 3520 V, requiring a 40 to 50 percent increase in its volume. The peak commutation current would increase in proportion to the increase of the maximum dc voltage because the commutation circuit impedance must be the same as the baseline to deliver rated power at 2200 V. Accordingly, the commutation capacitors, rectifiers, thyristors, and inductors must accommodate increased voltages and currents. The commutation capacitor volume would increase approximately 40 percent. The commutation inductor size would also be increased 40 percent. The same fuel-cell-type commutation thyristor design would be used in a modified converter. A revised snubber circuit design with additional cooling to handle the increased dissipation resulting from the higher peak current, would also be required.

The rectification mode current is estimated to impose a 33 percent increase in the diode dissipation, requiring a change from a 38-mm to a 52-mm inverter-type device in addition to increased cooling capability. This is not anticipated to be a major technical problem, and it is estimated that such a device could be developed within one year using existing technology.

The overall increase in bridge size, resulting from the increase in input capacitors, commutation capacitors, and commutation inductors, is estimated to be 20 percent. This change in size requires a major redesign, including a larger frame and internal bus structure. Therefore, an FCG-1 inverter bridge modified for wide-range voltage operation will not have production commonality with the baseline fuel cell version, and the modifications cannot be regarded as minor.

The series reactor would carry the same ac current as in the inverter mode because the ac voltage would be controlled and the maximum ac system VA rating would remain the same as in the fuel cell inverter system. The bridge output voltage would increase in proportion to the dc voltage range increase. This would be reflected in an increased insulation stress, which is of secondary impact on reactor size. Thus, the series reactors would remain the same size as in the baseline fuel cell inverter system.

The harmonic-cancellation transformer in the inversion mode is required to handle 1.0-per-unit current and relatively small harmonic voltages at the full load point. At minimum load (25 percent), the current requirement is low, but harmonic voltage requirement is high due to the impact of Pulse-Width-Modulation voltage control at a higher dc voltage. An increase of 20 to 25 percent in kVA was estimated for this application because the 1.0-per-unit current and end-of-charge voltage could be required simultaneously.

The output transformer requirements would be the same as for fuel cell inverter systems, and therefore no change is required.

Modified FCG-1 Converter Performance

The increased voltage and peak commutation current requirements described above result in a reduction of system efficiencies for the converter application as compared to the fuel cell inverter system. Table 4-3 summarizes these results for the boundary conditions at start and end of charge and discharge modes.

TABLE 4-3. RANGE OF EFFICIENCY FOR MODIFIED FCG-1 CONVERTER
27.6-MW SYSTEM (1.6:1 VOLTAGE RANGE)

<u>Mode</u>	<u>Operating Conditions</u>					
	<u>Start of Charge</u>	<u>End of Charge</u>	<u>Start of Discharge</u>		<u>End of Discharge</u>	
Voltage, dc	2850	3520	2860		2200	
Power level, %	100	100	100	25	100	25
<u>Components</u>	<u>Losses Contributed by Components</u>					
Converter bridges, %	2	2.8	2.1	6.9	1.5	3.6
Series reactors, harmonic transformer, output and harmonic filter, %	1.8	1.8	1.8	3.0	1.7	2.6
Cooling, control cabling, and miscellaneous, %	0.9	0.9	0.9	1.1	0.9	1.1
Total Losses, %	4.7	5.5	4.8	11.0	4.1	7.3
Overall efficiency, %	95.3	94.5	95.2	89.0	95.9	92.7
Program efficiency goal, %	95.0	95.0	95.0	90.0	95.0	90.0

Compared to the basic fuel cell inverter system, the full-load efficiency is estimated to be 95 percent average, rather than 96 percent. Part-load efficiency is estimated to be 90 percent average, rather than 92 percent. The increased peak commutation current, at part load, and increased dc voltage, at end-of-charge, cause the bridge losses to increase. Similarly, harmonic-cancellation transformer losses increase because these components must simultaneously support 1.0-per-unit current and the harmonic voltages resulting

from voltage control at end-of-charge. In the fuel cell application, this simultaneous application of maximum voltage and current does not occur.

FCG-1 Converter with Augmentation Selected

The results of the evaluation may be summarized as follows:

- Modification of the basic FCG-1 inverter bridge for converter operation over a 1.6-to-1 voltage range will increase the bridge size 20 percent. The increased input filter and commutation capacitor sizes cannot be incorporated in the basic bridge with minor modifications. This approach is borderline for the efficiency goals of 95 percent average full load and 90 percent average quarter-load (charge or discharge mode).
- Although no detailed study was made, it is estimated that a lower rated converter system (6.5 to 7 MW) could fit into the present FCG-1 bridge frame. Smaller and faster turnoff devices could be used to improve efficiency. The resulting system would be marginal for the cost goals.
- The FCG-1 bridge with augmentation has a higher performance potential than the FCG-1 bridge modified for extended range converter operation. It provides production commonality with the fuel cell inverter bridge and permits a better match with the requirements.
- The impact of the 1.7-to-1 voltage range associated with a 5-hour discharge, as compared to the 1.6-to-1 voltage range (10-hour discharge), increases the potential benefits of the augmented approach.

Having reviewed the estimated performance of the FCG-1 inverter system as a converter, United recommended that the preferred plan is to evaluate the

FCG-1 system with augmentation. This approach was discussed with the ERDA Project Manager on April 26, 1977, and the program was directed toward evaluation of the augmented system.

The recommendation for the augmented approach will:

- Permit use of the baseline FCG-1 inverter bridge without a major redesign.
- Reduce component stresses due to the decreased operating voltage range.
- Improve system efficiencies.
- Satisfy the goal of production commonality with the baseline fuel cell inverter system.

FCG-1 Converter System with Augmentation

The FCG-1 inverter system is operated in the inverter mode only. One module's rating is 9.2 MW with a maximum input dc power of 9.6 MW. When employed in an energy storage battery system, the system must operate as an inverter during the discharge cycle when energy is supplied by the battery to the utility line and as a rectifier during the charge cycle when energy is supply to the battery from the utility line.

The survey data from the battery developers indicated the requirement to operate over either a 1.6-to-1 or 1.7-to-1 dc voltage range during the charge cycle and a 1.3-to-1 voltage range during the discharge mode. This voltage range is dependent on the battery type and the ratio of charge time to discharge time. The FCG-1 converter version is capable of operating over a 1.3-to-1 dc voltage range. The augmenter extends the system's dc voltage range capability to meet the voltage requirements of the advanced energy storage batteries. The modified FCG-1 converter dc voltage capability and the voltage augmentation required for the various operating modes is given in Table 4-4.

TABLE 4-4. AUGMENTATION REQUIREMENTS FOR MODIFIED FCG-1 CONVERTER

Operating <u>Mode</u>	Voltage Range		Augmentation <u>Voltage Required</u>
	<u>Actual</u>	<u>Ratio</u>	
Discharge	2860 to 2200 V	1.3 to 1	0
Charge	3520 to 2200 V	1.6 to 1	660 Vdc
Charge	3740 to 2200 V	1.7 to 1	880 Vdc

Candidate Augmentation Techniques

There are two general classes of augmentation that can be employed in conjunction with the self-commutated converter system based upon the FCG-1 inverter. The first class comprises methods in which there is an energy exchange between the utility line and the battery through the augmentation equipment. These concepts include line-commutated and self-commutated converters, which can transfer energy in either direction. The use of these augments techniques can increase the power capability of the power-conditioning system because they function as parallel elements. The second class of augmentation comprises methods in which there is no supplemental energy exchange between the utility line and the battery. These concepts would include buck and boost regulators and cell stack switching. These techniques will not yield an increase in system power capability unless the converter bridges and output magnetics were uprated because they function as series elements.

PRELIMINARY EVALUATION

Each of the augmentation candidates selected for preliminary evaluation was examined for both the charge- and discharge-limited cases. The augmentation concepts considered were as follows:

- Line-commutated converter
- Self-commutated converter

- Buck/boost regulator
- Boost regulator
- Phase-controlled rectifier
- Dual FCG-1 inverter bridges
- Battery cell stack switching

Line-Commutated and Self-Commutated Converters

The self-commutated converter and the line-commutated converter are capable of both rectifier and inverter augmentation. For the 7-hour/10-hour battery cycle, the power-conditioning system capability is limited by capacity during the charge cycle and has excess capacity during the discharge cycle. Therefore, the inversion capability is not required and the line-commutated converter reduces to a phase-controlled rectifier. The phase-controlled rectifier would also be a better choice than the self-commutated converter operating in the rectifier mode on the basis of cost and efficiency.

Although the power-conditioning system capability is limited by its capacity during the discharge cycle for the 7-hour/5-hour cycle, the degree of disparity is not so severe as it is for charging for the 7-hour/10-hour cycle. Accordingly, it is desirable to consider concepts that permit both rectification during the charge cycle and inversion during the discharge cycle. The self-commutated converter augmentor in the rectifier mode during the charge cycle will be considered first. It would be in series with the main converter on the dc side, as shown in Figure 4-25, and would be designed to operate over the range of 0.3 to 0.4 pu dc voltage. It would be bypassed when dc voltage is less than 1.30 pu. It would cut in at 1.30 pu dc voltage and supply 0.30 pu voltage after the main converter bus voltage is reduced to 1.00 pu. The main converter in the 7-hour/10-hour cycle will then carry the variation up to 1.30 pu on its bus with 0.30 pu on the augmentation bus for a total of 1.60 pu dc voltage. In the 7-hour/5-hour cycle, the augmentor will then carry the voltage on up to 1.70 pu. The augmentor would have a nominal rating of approximately 30 percent of the main converter rating. To augment the discharge

mode, it is not feasible to switch over to a parallel connection of the dc side since this would require the augmenter to operate at 1.0 to 1.3 pu dc voltage instead of 0.3 to 0.4 pu. Commutation losses would be very high and component voltage ratings would have to be increased substantially. Therefore, the series connection must be retained during discharge, which means that the augmenter can be used to increase the discharge rate only when the battery voltage equals or exceeds 1.3 pu. This eliminates the concept from consideration because that condition does not exist for significant time periods for any of the battery systems.

Figure 4-25. Self-Commutated Converter Augmenter

The line-commutated converter, shown in Figure 4-26, is less restricted by the low dc voltage available during discharge. It could assist discharge with battery voltages down to about 1.15 pu; however:

1. Its dc side must incorporate switches to accommodate the bridge polarity change when changing from the charge to the discharge mode.

2. At 1.15 pu dc voltage, the augmenter would invert about 12 percent of the main converter power and require about 2.45 times this many kvars for power factor correction. This makes this approach no more attractive than the self-commutated converter approach.

Figure 4-26. Line-Commutated Converter Augmenter

Buck/Boost or Boost/Boost Regulator

Initial consideration was given to a buck/boost concept. This approach seemed applicable for the 7-hour/10-hour cycle where the system is charge-limited. The basic approach was to both buck and boost during the charge cycle. The converter voltage is bucked from 1.0 pu to meet the battery voltage requirements in the range from 0.85 to 1.0. The basic converter operates over the range from 1.0 to 1.3 pu. The converter voltage is boosted from 1.3 to match the battery voltage over the 1.3 to 1.45 charge range. Two thyristor commutation circuits, each capable of commutating essentially full current, are required. This concept increases the system cost and reduces the efficiency as compared to the straight boost regulator.

For the 7-hour/5-hour cycle, a boost/boost approach matched the requirements of this discharge-limited cycle. The boost/boost approach boosts the converter voltage on charge and boosts the battery voltage on discharge. Figure 4-27 shows one possible arrangement. The augments would boost the battery voltage during discharge from 0.85 to 1.0 pu at the converter terminals. The converter voltage would be boosted during charge to meet the 1.3 to 1.45 battery voltage range. Again, this approach would have twice the commutation circuits, each capable of commutating full current, as compared to the straight boost. This technique would add booster losses during both the charge and discharge cycles, whereas the straight boost losses were added during the charge cycle only. Therefore, this system has a higher cost and lower efficiency than the straight boost and can be eliminated.

Figure 4-27. Boost/Boost Regulator Augmentation

Boost Regulator

The boost regulator shown in Figure 4-28 was evaluated. This is a standard flyback approach. Although this concept does not increase the energy capacity of the power-conditioning system, it does have the ability to satisfy the wide dc voltage range requirements of the battery systems when used in

conjunction with the modified fuel cell converter. The boost regulator is used during the charge cycle only to boost the converter voltage from 1.3 pu to the maximum required by the batteries.

Figure 4-28. Boost Regulator Augmenter

This scheme does not result in an increase in system capability under any conditions. For the 7-hour/10-hour case, the system will therefore suffer in MW-hours delivered as compared to the phase-controlled rectifier, which does exhibit an energy increase for this charge-limited case.

For the 7-hour/5-hour cycle, the nominal charge and discharge rates are nearly identical. Since there is no economical way of reclaiming the added storage provided by energy augmentation schemes such as the phase-controlled rectifier, the boost approach becomes a contender.

Phase-Controlled Rectifier

The phase-controlled rectifier augmentor, as shown in Figure 4-29, could be employed with the modified fuel cell converter to satisfy the dc voltage requirements of the battery systems and increase the system's energy capacity during

the charge cycle of operation. Although the increased energy capacity cannot be utilized during the 7-hour/5-hour cycle, it can be used during the 7-hour/10-hour cycle, which is charge-limited. The augments would be in series on the dc side and would be designed to operate over the range of 0.3 pu dc volts for the 7-hour/10-hour case, and 0.4 pu for the 7-hour/5-hour case. During the entire discharge cycle and when the dc voltage is below 1.3 pu in the charge mode, the augments is bypassed with a dc contractor. The augments operation would be initiated at 1.3 pu dc voltage and supply 0.3 pu voltage after the main converter bus voltage is reduced to 1.0 pu. The main converter would then carry the variation up to 1.3 pu dc voltage on its bus with 0.3 pu on the augments bus for a total battery voltage of 1.0 pu. For the 5-hour/7-hour cycle, the augments would carry the voltage up to 1.7 pu. The augments would have a nominal rating of approximately 30 percent of the main converter rating.

Figure 4-29. Phase-Controlled Rectifier Augmentation

Dual FCG-1 Converter Bridges

The scheme considered was an ac side concept utilizing two parallel FCG-1 converter bridges. The block diagram for the configuration of this system is shown in Figure 4-30. This converter bridge is capable of operating over a

wide dc voltage range so long as the load current plus surge margins do not exceed the commutation circuit limits at the particular voltage level of operation. Thus, though the upper dc voltage level is determined by component ratings for a specific bridge design, the lower dc voltage limit can be lowered to achieve the necessary voltage range. This necessitates a reduction in the converter bridge ac power level because the commutation capability decreases as a direct function of dc voltage reduction.

Figure 4-30. Dual FCG-1 Converter Bridges

Battery Cell Stack Switching

Battery cell stack switching was the next augmentation concept evaluated. An example of this technique for a 7-hour/5-hour cycle, which requires a 1.7 to 1 dc voltage range capability, is presented in Figure 4-31. The configuration shown is for an effective three-cell stack in parallel at $4/3$ of one long stack voltage. Areas of concern, from a control standpoint, include the following:

1. At the switching points, the battery current must be reduced to zero so that the associated thyristors can recover. This means the battery voltage will change immediately due to the internal resistance and begin to drift, in a presently unpredictable way, either upward

or downward. Thus, there would not be an ensured voltage to work against when restarting. This cannot be assessed until more data is available regarding battery transient behavior.

2. When the switching thyristors are gated to resume charging or discharging, the converter dc bus voltage must be equal to the battery voltage to preclude ring-up from the converter dc filter bank plus stray inductance. Thus, the mode of control must shift from the normal one of controlling power according to demand to one that varies power to maintain the desired converter bus voltage. This is quite feasible in theory, but it will require development.
3. Since all of the current must flow through additional devices, added losses will still be a factor, both in charging and discharging.

Figure 4-31. Cell Stack Switching

Selection of Two Augmentation Concepts

The selection process for augmentation concepts for the 7-hour charge/10-hour discharge, and the 7-hour charge/5-hour discharge was made in the following manner:

1. Concepts were examined on fundamental bases to determine their applicability.
2. Technical feasibility was examined to determine any unknowns that would preclude their use.
3. The cost and MW-hour delivered of the most promising concepts were estimated. These estimates were based on a rough scaling from basic FCG-1 converter costs and other in-house studies.

The results of the 7-hour/5-hour studies are given in Table 4-5. The use of dc side augmentation, either self-commutated or line-commutated, was eliminated at step one because there are insufficient dc volts to permit operation during the inversion phase to permit use of the inversion capability. The use of cell switching was eliminated under step two because the knowledge of battery transient characteristics did not give sufficient assurance that the dc voltage could be adequately controlled within the required input range of the FCG-1 converter system.

The buck/boost regulator was eliminated at the beginning of step three because it did not offer any performance or cost advantages over the straight boost. The final three candidates were then compared on a cost-performance basis. For these studies, it was assumed that the magnetics were 10 MW-ac rating for all cases and could be overloaded 10 percent during the charge period without shortening the life, because of the cooler night temperatures. Based on these comparisons, the boost-only and the phase-controlled rectifier were selected. The boost-only was selected on the basis of having the lowest

cost/MW-hr, while the phase-controlled rectifier was selected to provide commonality with the selection for the 7-hour/10-hour cycle. Also, it is a simpler concept and more attractive from a performance standpoint than indicated by the preliminary screening.

TABLE 4-5 . PRELIMINARY SCREENING OF CONCEPTS
7-HOUR CHARGE/5-HOUR DISCHARGE

<u>Concept</u>	<u>Total Cost</u>	<u>MW-Hr Del</u>	<u>Cost/ MW-Hr</u>
Baseline FCG-1 converter system	1.0	1.0	1.0
DC side augmentation			
(1) Self-commutated inverter or line-commutated inverter		Inversion capability not usable because of insufficient dc volts	
Two-stage systems			
(2) Buck boost	>(3)	1.0	>(3)
(3) Boost only	~1.10	1.0	1.10
(4) Phase-controlled rectifier	1.18	1.0	1.18
AC side augmentation			
(5) Three additional fuel cell converter bridges in parallel	1.25	1.09	1.14
Miscellaneous			
(6) Cell switching		Ruled out because of uncertainty of control based on battery characteristics knowledge	

The results of the preliminary screening of the 7-hour/10-hour cycles are given in Table 4-6. Again, augmentation using self-commutated or line-commutated converters was eliminated at Step 1. In this case, inversion capability was not required and the basic requirements reduced to that for rectification only; therefore, the phase-controlled rectifier was a better choice. Cell switching was ruled out because of control uncertainty at Step 2. At Step 3, the buck/boost and the boost-only systems were eliminated because the additional MW-hours delivered by the phase-controlled rectifier during the charge cycle in this charge-limited system make this system more attractive. The phase-controlled rectifier approach also exhibits superior cost to the three additional fuel cell converter bridges and was selected for the 7-hour charge/10-hour discharge.

TABLE 4-6. PRELIMINARY SCREENING OF CONCEPTS

7-HOUR CHARGE/10-HOUR DISCHARGE

<u>Concept</u>	<u>Total Cost</u>	<u>MW-Hr Del</u>	<u>Maximum Rate of Charge</u>	<u>Cost/MW-Hr</u>
Baseline FCG-1 converter system	1.0	1.0	1.0	1.0
DC side augmentation				
(1) Self-commutated or line-commutated inverter	Inversion capability not required reduces to rectifier only			
Two-stage systems				
(2) Buck/boost	>(4)	1.0	1.0	>(4)
(3) Boost only	>(4)	1.0	1.0	>(4)
(4) Phase-controlled rectifier	1.15	1.15	1.15	1.0
AC side augmentation				
(5) Three additional fuel cell converter bridges in parallel	1.25	1.09	1.09	1.14

Miscellaneous

- (6) Cell switching Ruled out because of uncertainty of control based on knowledge of battery characteristics

Further Consideration of Multiple-Bridge Concepts

Examination of the three additional FCG-1 converter bridges in parallel showed that a more realistic comparison would allow the bridges to be run at their allowable rating and to increase the magnetics ratings to this level. The original comparison was made at the 9.2-MW power output level. The required dc voltage range for the 7-hour/10-hour cycle converter is 1788 to 2860 Vdc (1.6 to 1). As the minimum dc voltage decreases below the 2200-Vdc level, there are two effects on the converter bridge capabilities:

1. The ac voltage level must be reduced below that for the FCG-1 since the poles cannot generate this level with lower minimum dc voltage.

The permissible ac voltage level will be

$$V_{ac} = E_{min}/2,200 \text{ pu}$$

or since the minimum dc voltage will be 1,788 V for the 1.6 to 1.0 voltage ratio,

$$V_{ac} = .813 \text{ pu.}$$

2. Since commutation capability will be reduced, the peak ac current per pole must be reduced sufficiently to provide commutation margin.

Since the peak commutation capability is proportional to Vdc

$$I_{ac} = 1788/2200 \text{ pu}$$

and $I_{ac} = .813 \text{ pu.}$

Power at this dc voltage level is then

$$P_{ac} = .813 \times .813 = .66 \text{ pu}$$

per set of bridges.

More generally, the permissible current is

$$I_{ac} = \frac{E}{2200}$$

where

E = dc voltage in volts.

From the above, the general expression for permissible ac power based on FCG-1 ratings for six bridges in a system designed for 1788 to 2860 volt operation is

$$P = 2 \times .813 \times E/2200.$$

The plot for this is shown in Figure 4-32. The foregoing curve shows that this configuration can handle

$$P_{ac} = 1.62 \text{ pu}$$

at voltages of 2,200 dc and above with appropriately sized magnetics.

Figure 4-32. AC Power Limit Curve for Six Bridges

The approach for the 7-hour/5-hour cycle is the same as for the 10-hour cycle, and the numbers become

$$V_{ac} = .765 \text{ pu}$$

$$I_{ac} = \frac{E}{2200}$$

$$P_{ac} = 2 \times .765 (E/2200)$$

The power limit curve is similar to that for the 10-hour cycle except that

$$P_{ac} = 1.17 \text{ pu at } 1682 \text{ V}_{dc}$$

and

$$P_{ac} = 1.53 \text{ pu at } 2200 \text{ V}_{dc} \text{ and above}$$

The results of the comparison for a 7-hour/5-hour cycle are given in Table 4-7. This comparison shows that the average cycle efficiency (average charge efficiency and average discharge efficiency /2,) are approximately the same for the sodium chloride battery case considered, and the phase-controlled rectifier has a 13 percent lower cost per kWh delivered.

TABLE 4-7. COMPARISON OF POWER-CONDITIONING SYSTEMS
FOR 7 HOUR/5 HOUR CYCLE

<u>System</u>	<u>Discharge Rate</u>	<u>Cost/Rated kW*</u>	<u>Cost/kW-Hr Del**</u>	<u>Avg. Converter*** Cycle Efficiency For NaCl Battery, %</u>
Baseline FCG-1 Converter	1.0	1.0	1.0	---
Phase Controlled rectifier	1.0	1.18	1.16	95.6
Three addition bridges in parallel	1.17 at 1682 V _{dc} 1.52 at 2200 V _{dc}	1.18	1.33	95.4

Notes

* Based on kW delivered at start-of-discharge.

** Based on delivery of maximum kW during discharge.

*** Power-conditioner cycle efficiency = $\frac{\text{Average Charge Efficiency} + \text{Average Discharge Efficiency}}{2}$

The approach was initially used to compare cycle efficiencies, current practice is to use Cycle Efficiency = Discharge Efficiency + Charge Efficiency as a more representative measurement.

The results of the comparison for a 7-hour/10-hour cycle on the same basis are given in Table 4-8. The efficiency for both cycles are the same within the calculation error. The cost per kWh delivered for the phase-controlled rectifier is 20 percent lower.

TABLE 4-8. COMPARISON OF POWER-CONDITIONING SYSTEMS FOR 7-HOUR/10-HOUR CYCLE

System	Maximum Cycle Charge Rate	Discharge Rate	Cost/Rated kW*	Cost/kW Del**	Avg Converter*** Cycle Efficiency NaCl Battery, %
Fuel cell converter	1.0	1.0	1.0	1.0	-----
Phase-controlled rectifier	1.28	1.0	1.14	.89	96.2
Three additional bridges in parallel	1.63 V _{dc} > 2200V 1.32 V _{dc} = 1788V	1.63 V _{dc} > 2200V 1.32 V _{dc} 1788V	1.12	1.12	96.1

* Based on kW delivered at start-of-discharge.

** Since cycle is charge capacity limited, kW delivered is direct function of charge capability.

*** Power-Conditioner Cycle Efficiency = $\frac{\text{Average Charge Efficiency} + \text{Average Discharge Efficiency}}{2}$

This approach was initially used to compare converter cycle efficiencies; current practice is to use Cycle Efficiency = Discharge Efficiency + Charge Efficiency as a more representative measurement.

Considering the additional complexity of the six-bridge system versus the four-bridge plus phase-controlled rectifier, in addition to the cost benefits, the original choice of the phase-controlled rectifier over the additional bridges in parallel is justified.

DESIGN OF FINAL TWO CONCEPTS

Electrical circuit designs were made for the two augmentation concepts selected for further evaluation. Phase-controlled rectifier augmentor designs were developed for the 7-hour/10-hour, 1.6-to-1 dc voltage range (2200 to 3520 V) case and the 7-hour/5-hour, 1.7-to-1 voltage range (2200 to 3740 V). A boost regulator design was made for the 7-hour/5-hour, 1.7-to-1 voltage range (2200 to 3740 V). The circuit ratings were developed using analytical calculations and digital computer programs. The EAI hybrid simulator was used for verification of stresses and circuit performance.

Modified FCG-1 Converter

The converter system derived from modification of the FCG-1 inverter has the capability to operate in both modes of operation. The maximum ac power capability is dependent on whether the batteries are being charged or discharged. This power level is determined by the magnitude of the ac load current, which establishes stress levels in the output magnetics and in internal components within the converter bridge. The internal bridge components that establish the maximum ac power level include the semiconductor switch, which is composed of a main thyristor and a diode and the semiconductor fuse. This configuration is shown in Figure 4-31.

Figure 4-33. Converter Bridge Power Handling Components

During the discharge cycle, which is similar to fuel cell operation, the ac load current internal to the converter bridge is primarily conducted by the main thyristor at high power factor. This establishes a maximum ac power level of 9.2 MW during discharge. During the charge cycle, the load current in the bridge is primarily conducted by the main diode. In the FCG-1 inverter system the maximum ac power level would be limited to 5.8 MW during this

cycle by the rating of the 38-mm diode. For the battery application this device was changed to a 52-mm diode used in conjunction with an increased capacity cooler. With this configuration, the ac power limit of the semiconductor switch is 10 MW. The output magnetics designed for the fuel cell power conditioner are capable of handling 9.2 MW ac power. Since the balance of the power-handling components in the battery application are capable of handling 10 MW ac during the charge cycle, the output magnetics capacity was increased to this level. This established a common charge power capability of 10 MW ac. The required modifications are considered minor and consist of increasing insulation levels and current-carrying capacity. Table 4-9 offers a comparison of the ac power limits during the charge cycle for the basic FCG-1 inverter system and the modified fuel cell converter.

TABLE 4-9. AC POWER LIMITS DURING CHARGE CYCLE

<u>Component</u>	<u>Basic FCG-1 Inverter System</u>	<u>Modified FCG-1 Converter Version</u>
Semiconductor fuse	10 MW	10 MW
Semiconductor switch	5.8 MW	10 MW
Output magnetics	9.2 MW	10 MW

Phase-Controlled Rectifier Design

A system, Figure 4-34, consisting of two parallel three-phase bridges connected to the wye and delta low-voltage windings of the augments output transformer was selected. The transformer wye/delta configuration gives a 30-degree phase shift between rectifier bridges, which eliminates the 5th and 7th harmonics from the ac line. This configuration was chosen over a single-bridge system to minimize line filter requirements.

Figure 4-34. Phase-Controlled Rectifier, Functional Diagram

This is a standard design configuration used in dc power supplies. Output voltage control is obtained by varying the firing angle of the bridge thyristors.

In the circuit shown in Figure 4-34, the 13.8 kV ac output is reduced to 650 volts ac by transformer T1. The output of each set of secondary windings is fed to a three-phase phase-controlled thyristor bridge where the ac power is rectified to produce dc power. The output of the two bridges are paralleled through series inductors L1 and L2 to produce a dc voltage. The dc voltage is added to the output voltage of the converter during the charge mode. This voltage can be varied by controlling the firing angle of the inverter bridge thyristors.

Diodes D1 and D2 and contractor M provide a bypass function when augmentation is not required. SCR's 13 and 14 in conjunction with resistor RFD are used to force the battery voltage down during rapid reversal from charge to discharge.

Voltage Range of Operation

The converter design is the FCG-1 self-commutated inverter modified with 52-mm diodes to improve the rating in the rectifier mode. The harmonic-cancelling transformers, output reactor, and output transformer were also increased to give a 10-MW ac rating. This gives the battery converter design without augmentation a capability of 9.2 MW ac into the utility line and 9.6 MW dc into the battery. The dc operating range capability of 1.3 to 1 (2200 to 2860 Vdc) of the fuel cell design is retained.

The augments must supply the required differential voltage between the maximum operating voltage of the fuel cell power conditioner and the maximum operating voltage required for the energy storage batteries. For the 1.6-to-1 system voltage range (3520 V maximum), the augments must supply 3520 to 2860 V or 660 Vdc maximum output. For the 1.7-to-1 system voltage range (3740 V maximum), the augments must supply 3740 to 2860 V or 880 Vdc maximum output.

The maximum rectifier dc current required to satisfy battery systems evaluated is 3357 Adc, which was derived from the sodium chloride battery. Two parallel bridges are employed. Therefore, the dc current of each bridge is $3357/2$ which is equal to 1678 amperes.

The dc power is derived by multiplying the dc voltage times the dc current.

For the 1.6-to-1 design:

$$660 \text{ Vdc} \times 3357 \text{ A} = 2.212 \text{ MW maximum dc}$$

For the 1.7-to-1 design:

$$880 \text{ Vdc} \times 3357 \text{ A} = 2.95 \text{ MW maximum dc}$$

The bills of material for the designs are given in Tables 4-10 and 4-11. The detailed design of the two circuits that led to the development of those bills of materials is presented in Appendix A5.

TABLE 4-10. 1.6:1 PHASE-CONTROLLED RECTIFIER,
BILL OF MATERIAL

		Key to <u>Figure 4-34</u>
14	Thyristors: type C701, 1800 V rating	SCR-1-12 & 13, 14
2	Diodes: type A540; 1800 V, 1000 A rating	D1, D2
1	Transformer: 2.35 MVA Primary: wye; 13.8 kV, 97 A rms Secondary: delta-wye; 492 V, 1372 A rms	T1
2	AC contactors: NEMA 8; 600 V, 1400 A rms	N1 & N2
1	DC switch: no-load break; 3600 V, 4500 A	M
1	Down-forcing resistor: 10-second rating; 700 V, 160 A	RFP
2	Series inductors: 246 microhenry	L, L2
14	Divider resistors: 36,000 ohm, 100-watt	RD
16	Snubber networks	Not shown

TABLE 4-11. 1.7:1 PHASE-CONTROLLED RECTIFIER,
BILL OF MATERIAL

		Key to <u>Figure 4-34</u>
14	Thyristors: type C702; 2400 V rating	SCR 1-12 & 13, 14
2	Diodes: type A540; 2000 V, 1000 A rating	D1, D2
1	Transformer: 3.135 MVA Primary: wye; 13.8 kV, 131 A rms Secondary: delta-wye; 655 V, 1372 A rms	T1
2	AC contactors: NEMA 8; 700 V, 1400 A rms	N1, N2
1	DC switch: no-load break; 4000 V, 4500 A	M
1	Down-forcing resistor: 10 second rating; 900 V, 160 A	RFD
2	Series inductors: 447 microhenry	L1, L2
14	Divider resistors: 38,000 ohm, 120 watt	RD
16	Snubber networks	Not shown

Boost Regulator Design

The basic circuit configuration to be employed in describing the boost regulator operation is given in Figure 4-35. This circuit is the classical flyback type widely used for boost operation in power supplies. Operation is cyclic, and the current through the inductor LS is continuous. When SCR_1 is turned on, the voltage E_d is impressed across inductor LS and causes the current i_d to increase and energy to be stored in the inductor. When this current increases to a predetermined value, SCR_1 is turned off by its commutation circuit (not shown). The current i_d then starts to decrease, the voltage across inductor LS reverses and adds to E_d . Diode DS becomes forward biased by E_d plus the voltage across LS and conducts. The current I_c from the converter now flows through inductor LS and diode DS into the battery.

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Figure 4-35. Boost Regulator Circuit Configuration

The energy in the inductor discharges until the current i_d decreases to a preset minimum value. At that time, SCR_1 is turned on and the cycle repeated.

The current waveforms for the switching thyristor, battery, and series inductor are presented in Figure 4-36. When SCR_1 is conducting in steady-state operation, the inductor current can be expressed as:

$$i_d = i_d(0) + \frac{E_d t}{L} \quad \text{where relationships are defined in Figures 4-35, 4-36 and Table 4-12.}$$

Figure 4-36. Boost Regulator Current Waveforms

TABLE 4-12. BOOST REGULATOR,
BILL OF MATERIAL

8	Thyristors: type C712, 2200V rating
3	Diodes: type R622, 2200 V rating
3	Diodes: type R622, 2000 V rating
12	Diodes: type R9G2, 3000 V rating
20	Output filter capacitors: 4000 V, 55 A rms rating, 600 microfarad
10	Input filter capacitors: 3000 V, 67 A rms rating, 600 microfarad
1	Semiconductor fuse: 4000 V 1740 A
1	Series inductor: 1.25 millihenry
1	Commutation inductor: 32 microhenry
10	Commutation capacitors: 7.8 microfarad, 3740 V, 114 A rms
26	Divider resistors: 100 W
26	Snubber networks
1	DC switch: no-load break, 4000 V, 4500 A
1	Down Forcing Resistor, 880V, 325A for 10 sec.

Key to
Figure 4-37

SCR1 (3 in series)
SCR2 (3 in series)
SCR3 (2 in series)

DBP
DC
DS
CS1
CSO
Fuse
LS

LC
Not Shown
Not Shown
M
RFD

At time t_1 , the switching thyristor (SCR_1) is turned off, which opens the current in this branch. The current into the battery becomes:

$$i_L = i_d(0) + \frac{E_d t_1}{L} - \frac{(E_L - E_d)t}{L}$$

Just prior to turning SCR₁ on again for the next cycle (Time T), the inductor current can be expressed as:

$$i = i_d(0) + \frac{E_d t_1}{L} - \frac{(E_L - E_d) t_2}{L} = i_d(0) + \frac{E_d t_1 (E_L - E_d) t_2}{L}$$

In steady-state operation of the boost regulator, this current must be equal to $i_d(0)$. Therefore,

$$i_d(0) = i_d(0) + \frac{E_d t_1 - (E_L - E_d) t_2}{L}$$

The cycle period duration is equal to T, which equals $t_1 + t_2$. The thyristor conduction time (t_1) and the thyristor off time (t_2) can be solved as a function of the battery voltage, converter voltage, and the period of a cycle of operation.

$$t_1 = \frac{T(E_L - E_d)}{E_L} \text{ and } t_2 = \frac{E_d T}{E_L}$$

For the 1.7-to-1 system voltage range the maximum battery voltage (E_L) is 3740 Vdc, while the maximum converter operating voltage (E_d) is 2860 V. The maximum average dc current (I_d) is 3357 amperes and the frequency of operation is 240 Hz. These values, in addition to the equations developed above, were employed in generating the detailed design of the boost regulator, which is presented in Appendix A6. The functional schematic and the bill of material that evolved from this design are given in Figure 4-37 and Table 4-12.

Figure 4-37 shows a more detailed circuit diagram. In addition to the basic elements shown in Figure 4-36, the filters, commutation circuitry, and bypass network is given. As the basic circuit operation has previously been described, discussion will be limited to the commutation circuit and by bypass network.

Figure 4-37. Boost Regulator Functional Diagram

The commutation capacitor is charged from the converter through diode DC to the polarity shown prior to operation. When it is desired to turnoff SCR₁ at no load, SCR₂ is gated on. This causes capacitor CC to discharge through the path consisting of inductor LC and SCR₂. The resonant action of capacitor CC and inductor LC will cause capacitor CC to become charged in the opposite direction. SCR₂ is then turned off by the reverse voltage of capacitor CC and further oscillation through the path is prevented. Capacitor CC now discharges through diodes DC and BSP and inductor LC. This reverse biases SCR₁ and commutates it off. Under load conditions, the circuit action is more complicated, and the inductor current is diverted away from SCR₁ into the path consisting of capacitor CC and diode DC and returned to the converter via the negative conductor. After SCR₁ is turned off by the reverse bias from DBP, the capacitor CC will be charged up in its original direction by the converter.

The contactor M is closed during discharge operation and periods of charge operation where the converter voltage range is sufficient. The function of the contactor is to eliminate the series losses of the boost regulator. SCR_3 and the down forcing resistor are used when rapid reversal from the charge mode to the discharge mode is desired.

Performance Analysis of Augmented Converter Systems

An existing digital computer performance analysis program was used for determination of the converter system efficiency. The program calculates the individual component losses as a function of the power and voltage operating levels.

New programs were developed to evaluate the efficiency of the phase-controlled rectifier augments. One program is used for the 1.7-to-1 voltage ratio, while a second is used for the 1.6-to-1 voltage ratio. Although these augments operate in an identical manner, two programs were required because of the different electrical component choices. These programs were written as subroutines to be used with the converter system program.

In these programs, each component's loss is defined, in equation form, as a function of either the voltage or current to which it is subjected. The total loss for the augments is obtained by summing all of the individual component losses and multiplying the result by 1.1 to account for termination and bus losses. This multiplication factor was derived from previous experience with similar conversion equipment. The augmentation subroutines employed for the loss calculations are presented in Appendix A5.

Each of the component loss equations is developed below with reference to the circuit diagram shown in Figure 4-34.

The maximum dc current in the series inductors (L1 and L2) is obtained by dividing the maximum dc power by the minimum dc voltage:

$$I_{dc} = 9.6 \times 10^6 \text{ W} / 2200 \text{ V} = 4364 \text{ A}$$

Each series inductor must conduct one-half of this value (2182 A dc). The maximum power loss can be determined as follows:

$$\begin{aligned} P_{loss} &= I_{dc}^2 R \\ &= 2182^2 \times .86 \times 10^{-3} = 8.2 \text{ kW} \end{aligned}$$

The power loss as a function of dc current can then be ratioed from this maximum value and expressed as follows:

$$\begin{aligned} P_{loss} &= 8.2 \times (I_{dc}/4364)^2 \text{ kW} \\ &= 4.306 \times 10^{-7} I_{dc}^2 \text{ kW} \end{aligned}$$

The thyristor losses (SCR1-12) are a function of the device's forward voltage drop and the current conducted by the unit. The forward voltage drop, from the General Electric C701 data sheet, can be expressed as:

$$V = .0546 (I + 350)^{.4282} \text{ volts}$$

Therefore, the average power loss of each SCR for a 120-degree conduction period is:

$$P_{loss} = 1/3 \times .0546 I (I + 350)^{.4282} \text{ watts}$$

Expressing I as a function of the dc current (I_{dc}) yields:

$$P_{loss} = .0091 I_{dc} (I_{dc}/2 + 350)^{.4282} \text{ watts each device.}$$

$$P_{loss} = 1.092 \times 10^{-4} I_{dc} (I_{dc}/2 + 350)^{.4282} \text{ kW for all 12 devices.}$$

The transformer losses (T1) comprise iron-core losses and copper losses. The iron-core losses can be expressed as a function of the ac voltage level, while the copper losses can be expressed as a function of the current being conducted. The coefficients employed in the subroutine were obtained by ratioing from previous detailed transformer designs based on the transformer MVA rating of 3.03 MVA. The following expressions were derived from the component design:

$$P_{\text{core}} = 13.36 V_{\text{ac}}^2 \quad \text{kW}$$

$$P_{\text{copper}} = 8.139 \times 10^{-7} I_{\text{dc}}^2 \quad \text{kW}$$

The auxiliary losses are estimates expressed in percent of the phase-controlled rectifier maximum MVA capability. These estimates are derived from the fuel cell power conditioner development and incorporate judgements of the effects of less complexity, smaller size, and different circuitry:

<u>Source</u>	<u>Loss, %</u>
Logic	.05
Cooling	.05
Bus	.06
Miscellaneous	<u>.75</u>
	.91% Total

This percent loss yields $.0091 \times 3.03 \text{ MVA} = 27.6 \text{ kW}$. This value is used as a constant in the subroutine. The subroutine for the 1.7-to-1 phase-controlled rectifier augmentor was developed in an identical manner using the voltage and current levels as well as component characteristics in effect for that design.

Efficiency of Final Two Concepts

Because the augmenters operate only during the charge cycle, two representative load points of the cycle are provided for comparison of the power conditioning system efficiency for each of these concepts. The representative load points were selected from the sodium chloride 7-hour/5-hour battery case, since the boost regulator was not a contender for the 7-hour/10-hour cycles. These test conditions are a dc voltage of 3100 V at a dc power of 6.51 MW for the first case and a dc voltage of 3600 V at a dc power of 1.8 MW for the second case. These points are identified on the battery profile shown in Figure 4-38.

Figure 4-38. Power-Conditioner System Efficiency - Load Points

The losses for the modified FCG-1 converter and the phase-controlled rectifier were determined through the use of the previously discussed performance analysis computer program and the applicable 1.7-to-1 phase-controlled rectifier subroutine. A subroutine for the use with the performance analysis program was not developed for the boost regulator augmentor. Therefore, the component losses for this augmentor were manually calculated for each of the load points. The modified fuel cell power conditioner component losses when incorporated with the boost regulator were determined by the performance analysis program at the applicable voltage and current levels. The derivation of the discrete component losses for the boost regulator is presented in Appendix A8.

The results of the efficiency analysis are presented in Table 4-13. With the phase-controlled rectifier, the modified fuel cell converter portion can be operated at a lower dc voltage, and supplemental energy is supplied by the augmentor. The phase-controlled rectifier approach is 0.8 percent more efficient at high power, whereas the boost regulator is 0.6 percent more efficient at the low power point. The methods used in the calculation of the phase-controlled rectifier are more conservative and are of a more detailed nature. Therefore, the actual advantage over the boost regulator augmentor at high power would increase and the boost regulator augmentor advantage at low power would decrease.

TABLE 4-13. AUGMENTER EFFICIENCY COMPARISON CHART
BOOST REGULATOR VS 1.7:1 PHASE-CONTROLLED RECTIFIER

Augmenter	V Battery, V	V Converter, V	Battery, MW	Loss FCG-I, kW	Loss Augmenter, kW	Total System Loss kW	System Efficiency, %
Boost regulator	3100	2860	6.51	292	40	332	95.2
Phase controlled rectifier	3100	2220	6.51	197	73	270	96.0
Boost regulator	3600	2860	1.8	181	31	212	89.5
Phase controlled rectifier	3600	2720	1.8	165	60	225	88.9

System Cost Estimates

Cost estimates were made for the battery power conditioner configurations under consideration to aid in the selection of the best approach to battery power-conditioning. The cost was based upon delivery of 150 9.2-MW modules in 1982. The quantity of 150 per year was assumed to reflect the cost of a production manufacturing facility. The costing is projected to 1982 to allow for the maturity of power semiconductors. Estimates are in 1977 dollars. This estimate makes a number of assumptions concerning production quantity, manufacturing approach and manufacturing facility which are considered to be reasonable at this time. A revised estimate, reflecting specific assumptions should be made at the time any future firm hardware requirement is established.

The modified FCG-1 converter system portion of the costs was derived from previous United Technologies cost studies with suitable changes to account for the modifications for the battery applications. Component and subsystem costs were developed through use of catalog data and vendor quotes and projections. Labor costs were derived from assembly times for similar hardware. The level of detail for these estimates was similar to that shown for the augmentation systems shown in Appendix A-7. The following elements were included in the cost estimate for the converter system portion of the overall power-conditioning system:

- 3 converter bridges
- 2 harmonic-cancelling transformers
- 9 series reactors
- 1 output transformer
- power wiring
- controls
- ac switchgear and protection
- dc breaker

The selling price for the modified self-commutated converter system portion was estimated to be \$59/kW.

The material costs for the three augmenters studied were based upon the materials lists from the design studies. Labor costs were derived from United's experience in the fabrication and assembly of similar hardware, a multiplying factor of 1.5 was assumed to convert augments-manufacturing cost to selling prices. This factor is based on a study of the relationship between selling price and labor, material and factory overhead for similar products. Results of this study are shown in Figure 4-39. This 50 percent mark-up provides for selling, engineering, and general administration expenses plus taxes and profit. Obviously, mark-ups in the early stages of production would be considerably higher, but this estimate is considered reasonable for a study of mature production cost at this stage of development. A breakdown of the electrical components, mechanical components, and labor cost portions of the manufacturing costs for the augmenters is given in Table 4-14. Further detail is provided in Appendix A-7.

NOTE: DATA FROM 1969 CORPORATE TAX RETURNS

Figure 4-39. Nominal Manufacturer's Markup

TABLE 4-14. COMPARISON OF ESTIMATED AUGMENTER COSTS

<u>Augmenter</u>	<u>Electrical Components Costs, \$</u>	<u>Mechanical Components Costs, \$</u>	<u>Labor Costs, \$</u>	<u>TOTAL MANUFACTURING COSTS, \$</u>
1.6-to-1 Phase-controlled rectifier	38,110	7,890	6,506	52,506
1.7-to-1 Phase-controlled rectifier	43,634	7,890	6,506	58,030
Boost regulator	61,785	8,758	7,593	78,136

The selling prices of the complete battery power-conditioning systems are given in Table 4-15. For the 7-hour/5-hour cycles, the phase-controlled rectifier augmentation approach is 5 percent less expensive than the boost regulator approach. Although the boost regulator was not a candidate for the 7-hour/ 10-hour cycle, the phase-controlled rectifier would also be lower in cost for this cycle.

TABLE 4-15. COMPARISON OF ESTIMATED POWER-CONDITIONING SYSTEM COSTS

<u>System and Cycle</u>	<u>Selling Price, \$/kW in 1977 dollars</u>		
	<u>Modified FCG-1 converter</u>	<u>Augmenter</u>	<u>Total</u>
<u>7-hour/5-hour cycle</u> (1.7-to-1 voltage ratio)			
Phase-controlled rectifier	59	9.50	68.50
Boost regulator	59	12.75	71.75
<u>7-hour/10-hour cycle</u> (1.6-to-1 voltage ratio)			
Phase-controlled rectifier	59	8.50	67.50

The cost goal for this program was 60 \$/kW in mid-1975 dollars. Assuming an average inflation rate of 8 percent per year, the 60 \$/kW would inflate to \$68/kW in 1977 dollars. Thus, the estimated selling price of the phase-controlled-rectifier augmentation FCG-1 converter system meets these goals.

Modified Simulator for Augmented Battery Application

The hybrid simulator model of the converter system required modification to facilitate the evaluation of the augmented power-conditioning system employed in an energy storage battery. These changes consisted of altering the dc voltage source and adding the necessary digital program and analog components for the model of the phase-controlled rectifier augments. The resultant model emulates a power-conditioning system consisting of the elements shown in the block diagram of Figure 4-40. The dc voltage source in the fuel cell model consists of a function generator that exhibits the characteristics of a current-dependent voltage source. For the battery application, this dc source was changed to a fixed voltage source that was adjusted to achieve the desired dc voltage level for each case. The analog models of the dc source and the rectifier augments, in addition to the defining differential equations of the circuit, are given in Appendix A9. The models for both the 1.6-to-1 and 1.7-to-1 phase-controlled rectifier augments are similar except for the values of the series inductors and the turns-ratio of the transformer.

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Figure 4-40. Block Diagram of Fuel Cell Power Conditioner with Rectifier Augmentation

Implementation of the necessary logic for the phase-controlled rectifier on the analog portion of the hybrid computer, within the restriction of available analog logic, required that the commutation circuit of each converter power-pole be deleted. The behavior of the commutation circuit and its effects on the power-conditioning system interfaces have been extensively evaluated in previous designs.

The boost regulator augmentor model was also developed but not implemented on the computer because the phase-controlled rectifier was more promising at the time of completion of the model. The resultant circuit configuration, differential equations, and applicable logic for implementation are also presented in Appendix A9 for possible use in future applications.

The cases evaluated on the Hybrid Simulator and a listing of available data is presented in Appendix A10. A representative set of data for the 1.6:1 phase-controlled rectifier augmentation is also given.

Phase-Controlled Rectifier Selected as Final Concept

The preliminary screening of concepts indicated that the phase-controlled rectifier and boost regulator concepts were the leading candidates for the 7-hour/5-hour cycle, whereas the phase-controlled rectifier is the best selection for the 7-hour/10-hour cycle.

A comparison of these system concepts was made to select the final concept to be employed in conjunction with the modified fuel cell converter. The salient points considered in this comparison were:

- Efficiency
- Selling price
- Development cost

The comparison of each of these topics for the two augmenters is discussed below. The results of the comparison are summarized in Table 4-16.

TABLE 4-16. COMPARISON OF PHASE-CONTROLLED
RECTIFIER WITH BOOST REGULATOR *

<u>System</u>	<u>System Efficiency in Percent</u>		<u>Relative</u>
	<u>During Charge</u>		<u>Selling Price, \$kW</u>
	6.5MW	1.8 MW	
Phase-controlled rectifier augments	96	88.9	1.0
Boost regulator	95.2	89.5	1.05

*For 7-hour/5-hour discharge 1.7-to-1 dc voltage ratio

Efficiency

The 7-hour/5-hour sodium chloride battery, which requires 1.7-to-1 dc voltage range augments power conditioner, was used to define the evaluation load points. As shown in Table 4-16, conditioning system efficiencies are approximately the same for both augmenters, with the phase-controlled rectifier concept more efficient at the elevated power level and the boost regulator system more efficient at the reduced power level. The reduced power level occurs only with batteries that have a taper-charge period. Also, the taper charge with reduced power levels exists for a relatively short duration of the total charge cycle time. Therefore, on an entire charge-cycle basis, the average cycle efficiency with the phase-controlled rectifier augments will be greater than that achieved with the boost regulator because elevated power levels exist for the major portion of the charge cycle time. For the 7-hour/10-hour cycle, the same comments would also apply.

Cost

As previously discussed under system cost estimation, a cost estimation based upon 150 systems per year in 1982 was performed. As shown in Table 4-16, the relative dollars per kW selling price of the boost regulator augmented system is 5 percent more than the 7-hour/5-hour cycle phase-controlled rectifier augmented system.

Although the boost regulator was eliminated during the preliminary screening process for the 7-hour/10-hour cycle, the selling price is based on discharge \$/kW and would be the same for the boost case as the 7-hour/5-hour case of Table 4-16, while the phase-controlled rectifier augments is reduced to 2%. The phase-controlled rectifier costs 6 percent less than the boost regulator. When the 15 percent additional energy contribution during the charge cycle of the boost regulator is factored into the analysis, the phase-controlled rectifier augments is clearly the winner and the initial screening results are confirmed.

Development Cost

The phase-controlled rectifier augments concept employs a mature technology that can be incorporated with a minimum of development effort. The phase-controlled rectifier SCR bridges, transformer, and ac switchgear are standard high-volume production units that are readily available as assembled items that can be integrated into the desired system configuration. The boost regulator augments employs complex circuitry, specially designed magnetics, and innovative power semiconductor use. Control techniques and their implementation would require development with either augments concept. However, the uncertainties associated with the phase-controlled rectifier are significantly less than those encountered with the boost regulator. Therefore, the boost regulator requires a significantly greater development effort than the phase-controlled rectifier approach.

In summary, the phase-controlled rectifier augments is more attractive than the boost regulator in the required application for the power-conditioning

system used with advanced energy storage batteries. The favorable attributes of the phase-controlled rectifier augmenter as compared to the boost regulator include the following:

- Higher overall cycle efficiency
- Lower cost
- Lower development cost and risk
- Reduced complexity
- Increased system energy capacity for charge-limited system
- Optimum for both cycles considered

Performance of Phase-Controlled Rectifier Augmented Converter

The performance of the selected phase-controlled rectifier augmented converter was evaluated for the six advanced energy storage batteries. This evaluation was performed using a cycle analysis technique in conjunction with the performance analysis program. Details of this technique are given in Appendix A11.

This evaluation allowed the determination of the power conditioning cycle efficiency and energy inputs for the charge and discharge cycles of operation. Each of the six battery types was analyzed for both the charge-limited (typically 7-hour/10-hour) and discharge-limited (typically 7-hour/5-hour) cases, which yields a total of 12 primary cases developed. The battery system evaluation cases are identified in Table 4-17. The data derived from the cycle performance analysis for these cases is presented in Table 4-18. This data includes the ac MW-hr, dc MW-hr, power-conditioner loss, and power-conditioner efficiency during both the charge and discharge cycles of operation.

TABLE 4-17. CYCLE PERFORMANCE ANALYSIS CASE IDENTIFICATION

<u>CASE</u>	<u>SYSTEM</u>
1	Sodium sulfur type 1, 7-hr/5-hr, discharge-limited
2	Sodium sulfur type 2, 7-hr/5-hr, discharge-limited
3	Sodium chloride, 7-hr/5-hr, discharge-limited
4	lithium/metal sulfide 2, 10-hr/5-hr discharge-limited
5	Lead acid, 7-hr/5-hr discharge-limited
6	Zinc chloride, 5-hr/5-hr charge-limited
7	Sodium sulfur type 1, 7-hr/10-hr charge-limited
8	Sodium sulfur type 2, 7-hr/10-hr charge-limited
9	Sodium chloride, 7-hr/10-hr charge-limited
10	Lithium/metal sulfide, 10-hr/10-hr charge-limited
11	Lead acid, 7-hr/10-hr charge-limited
12	Zinc chlorine, 5-hr/10-hr charge-limited

TABLE 4-18. CYCLE PERFORMANCE ANALYSIS RESULTS

<u>Case</u>	<u>AC, MW-HR</u>	<u>DC, MW-HR</u>	<u>CHARGE Loss, MW-HR</u>	<u>Efficiency, %</u>	<u>AC, MW-HR</u>	<u>DISCHARGE DC, MW-HR</u>	<u>Loss MW-HR</u>	<u>Efficiency %</u>	<u>CONVERTER CYCLE LOSS, MW-HR</u>
1	66.75	64.18	2.58	96.2	46.17	48.06	1.88	96.1	4.46
2	57.37	55.09	2.27	96.0	46.20	47.97	1.77	96.3	4.04
3	59.25	56.30	2.96	95.0	45.33	47.12	1.79	96.2	4.75
4	83.86	80.37	3.49	95.8	44.95	46.73	1.78	96.2	5.27
5	59.82	57.26	2.57	95.7	44.33	46.08	1.75	96.2	4.32
6	50.14	48.17	1.95	96.0	37.08	38.54	1.46	96.2	3.41
7	71.06	68.43	2.65	96.3	53.92	56.33	2.41	95.7	5.06
8	65.97	63.45	2.51	96.2	55.27	57.53	2.27	96.1	4.78
9	78.33	74.71	3.62	95.4	66.71	69.41	2.71	96.1	6.33
10	87.24	83.64	3.60	95.9	60.59	63.17	2.59	95.9	6.19
11	85.91	82.58	3.33	96.1	67.85	70.63	2.78	96.1	6.11
12	50.02	48.10	1.92	96.2	39.55	41.47	1.91	95.4	3.83

For these initial evaluations, supplemental augmentation was employed only as required by the battery profile during the charge mode. That is, whenever the battery voltage schedule exceeded the maximum operating capability of the

main converter (2860 V), the applicable augments operation was initiated. The phase-controlled rectifier used was either the 1.6-to-1 or 1.7-to-1 unit, depending on the system requirements. The converter voltage was lowered to equal the required battery voltage minus the augments voltage, with a minimum limit of 2200 Vdc, which is the minimum operating voltage capability of the modified fuel cell converter. The converter voltage was then varied as required to meet the particular battery voltage profile.

The results of the calculations show that the phase-controlled rectifier augmented fuel cell converter exceeds the 95 percent efficiency goal for both the charge and discharge cycles for all six advanced batteries. This analysis is addressed mainly to the power conversion system characteristics. The resulting MW-hour discharge capability of the battery/converter system studied is a function of United's interpretation of the data supplied by the manufacturers. Apparent variations in the battery efficiencies indicate a need for further work in this area.

One case was run to allow the comparison of the use of a 1.7-to-1 (880 V output) phase-controlled rectifier when the battery system actually required a 1.6-to-1 (660 V) augments. The comparative data generated are given in Table 4-19.

TABLE 4-19. COMPARISON OF PHASE-CONTROLLED RECTIFIER AUGMENTERS

Case	AC, MW-HR	DC, MW-HR	CHARGE Loss, MW-HR	Efficiency, %	AC, MW-HR	DISCHARGE DC, MW-HR	Loss MW-HR	Efficiency %	CONVERTER CYCLE LOSS, MW-HR
1.6 Aug.	78.33	74.71	3.62	95.4	66.71	69.41	2.71	96.2	6.33
1.7 Aug.	78.35	74.72	3.64	95.4	66.70	69.40	2.70	96.2	6.34

This comparison shows that no performance loss is incurred when a phase-controlled rectifier designed for a 1.7-to-1 voltage ratio is used for a 7-hour/10-hour, 1.6-to-1 voltage ratio application as compared to a phase-controlled rectifier designed for the 1.6-to-1 ratio.

The use of augmentation in a selective manner can increase the system's energy (MW-hr) capacity for the charge-limited cases by incorporating the augments whenever the battery voltage exceeds 2200 Vdc during the charge cycle. The converter is then operated at its minimum voltage (2200 V), while the augments supplies the differential voltage required up to its maximum output limit. The converter voltage is then increased as needed to satisfy the voltage schedule.

The use of selective augmentation at the 2200 V level permits an improved utilization of the self-commutated converter during the charge portion of the cycle. The converter system is power-limited by internal components to provide 9.6 MW dc in the charge mode. The battery system is matched at the start of charge to the converter rating. For normal augmentation, the battery is sized to match the self-commutated converter rating of 9.6 MW dc at 2860 volts and its augments used above 2860 V. In selective augmentation, the self-commutated converter provides 9.6 MW at 2200 V and the phase-control rectifier provides a maximum additional 2.7 MW at the battery match point. The power requirements during the remainder of the cycle are such that this can be accomplished without increasing the phase-controlled rectifier rating. However, when the augments is operated at less than full output voltage, there is a lagging var demand by the augments.

The var demand for the phase-controlled rectifier augments operated in the phase back mode is a function of the maximum augments output voltage, actual augments output voltage level, and the phase back angle of the control thyristors:

$$\phi = \cos^{-1} (V_o / V_{aug})$$

Where ϕ = phase back angle = ϕ

V_o = augments dc voltage output

V_{aug} = augments maximum dc voltage output

The var demand can then be expressed as follows:

$$Q = (1.052 V_{aug} \times I_{dc} \sin \phi / 10^6) \text{ Mvar}$$

This lagging var demand can be supplied either by the utility line or by the converter. When supplied by the converter, a reduction in the converter's power capacity is required for this portion of the cycle to keep the power-conditioning system within its rating of 10 MVA. This relationship can be expressed as follows:

$$P = (10^2 - Q^2)^{\frac{1}{2}}$$

Where P = allowable real power in MW

Q = var demand of the augments in Mvar

The 7-hour/10-hour sodium chloride battery was evaluated as an example of the use of selective augmentation. The results show that more optimum augmentation schedules can increase system energy delivery to the utility by 6 to 10 percent for the 7-hour/10-hour cycle without sacrifice of efficiency, as presented in Table 4-20.

TABLE 4-20. SELECTIVE AUGMENTATION COMPARISON
SODIUM CHLORIDE, 7-HOUR/10-HOUR EXAMPLE

<u>Augmenter Design Voltage</u>	<u>AC MW-Hours Discharge</u>	<u>Power-Conditioner Cycle Loss, MW-Hours</u>	<u>Discharge</u>	<u>Percent Efficiency Charge</u>
1.6/1 (1.6/1 at soc*)	66.7	6.3	96.1	95.4
vars from utility (1.7/1 at soc)	73.7	6.7	96.2	95.6
vars from utility (1.6/1 at soc)	73.7	6.9	96.2	95.4
vars from converter	70.8	6.6	96.2	95.5

*start of charge

SECTION 5

TASK 2 – TEST SELF-COMMUTATED CONVERTER FEATURES

SECTION 5. TASK 2 - TEST SELF-COMMUTATED CONVERTER FEATURES

INTRODUCTION

This section describes the results of United's work leading to the successful conclusion of Task 2 - Test Self-Commutated Converter Features. This effort was concluded with a demonstration performed on May 26, 1977, witnessed by the DOE Program Manager, J. Charles Smith, and other DOE and EPRI representatives and subsequently reported as Milestone No. 3 in report FCR-0518.

Task Objective

The program for evaluation of converter based on the 27.6-MW Inverter System, DOE (49-18)-2122, requires that the features of a self-commutated converter (SCC) be demonstrated in megawatt-scale hardware. The fundamental ability of an SCC to switch rapidly from the rectification mode to the inversion mode (without dc polarity reversal) was a principal feature to be demonstrated.

Demonstrated Features

- The ability to operate at unity power factor without power factor correction capacitors - This reduces installed cost and minimizes resonance with the utility network.
- The ability to convert from the charge to the discharge mode without a dc polarity change - This feature minimizes the cost of dc switch gear and permits rapid reversal.

- The ability to supply continuously variable leading or lagging vars within the kVA rating of the machine during charge or discharge and at zero real power - This feature allows use of the converter to control distribution system voltage and the power factor presented to the transmission line. This feature reduces the cost of power factor correction and reduces transmission line losses.
- The ability to cancel lower-order harmonics in a low-voltage harmonic-cancellation transformer - Harmonic cancellation minimizes the size of any filter required to meet power quality requirements; consequently, it minimizes resonance with the utility network. The cancellation of harmonics in low-voltage magnetics permits the use of nearly standard output transformers to interface with the variety of distribution system voltages.
- The ability to operate through most ac system voltage transients and to commute off for all other system transients except severe lightning strokes under worst-case loading - This feature minimizes interruptions of power flow to or from the battery system. In addition, the self-commutated system does not require opening a dc breaker in the event of ac voltage excursions; therefore, fuses can be utilized for dc system protection.
- The ability to provide trickle charge with continuous current and minimum ripple - This feature makes the self-commutated converter suitable for all modes of battery charging.

TEST HARDWARE DESCRIPTION AND CAPABILITIES

Megawatt-Scale Converter Systems

A megawatt-scale converter was modified to perform the basic test program. It was constructed as part of the inverter development program at United and

had undergone extensive testing for United's 27.6-MW program, including 169 hours of parallel operation with the utility line. Figure 5-1 shows the 0.5-MW development converter. It consists of two 900-kW, three-phase converter bridges with one thyristor in each position; the output magnetics (harmonic-cancellation transformer, series reactors, and output transformer) are sized to match the capacity of a 0.5-MW dc power supply located in the high-voltage laboratory. The outputs of the development converter bridges are phase shifted 30 degrees and then added in the harmonic-cancellation transformer. This approach cancels the 5th and 7th harmonics. The 11th and 13th harmonics are the first to appear.

Figure 5-1. 0.5-MW Development Converter

Test results from a 1-MW pilot inverter system were used to provide experience with utility line transients and additional data on var control. The inverter was fabricated as part of a 1-MW fuel cell pilot plant. The purpose of the pilot plant is to demonstrate the features and efficiency potential of the 27.6-MW fuel cell power plant. The system includes three 400-kW inverter

bridges and 1-MW output magnetics. Power is supplied to this system from a 0.5-MW power supply or from the 1-MW pilot dc fuel cell module. Figure 5-2 shows a picture of the 1-MW pilot inverter.

Figure 5-2. 1-MW Pilot Inverter

Facilities

The testing was conducted in the high-voltage laboratory located within United's fuel cell facility at South Windsor, Connecticut. The high-voltage laboratory was designed for testing power conditioner systems in the megawatt range. The laboratory is tied to a 14.4-kV Connecticut Light and Power Company line. Test control is accomplished remotely from control consoles located in a mezzanine above the test floor.

MODIFICATIONS TO THE 0.5-MW DEVELOPMENT CONVERTER SYSTEM

DC Load Bank

The existing hardware did not include a storage battery, so a power supply and a dc load bank were used to provide a source and a sink, respectively. An existing roof-mounted 200-kW dc load bank was rewired in parallel with the existing 500-kW dc power supply to provide this feature. The load bank was constantly energized during the demonstration to provide an adequate sink capability on a transient basis.

Controls and Logic

The controls and logic were modified to provide:

- Operation in the rectification mode
- Control of rate-of-change of power for the transient tests
- Remote operation from the control room
- Interfacing signals for the added digital meters

These modifications required the addition of eight dual operational amplifier chips and one multiplier function chip with associated resistors and capacitors. This is the equivalent of one additional 6-inch by 3-inch logic circuit board. Additional minor changes were made in the basic control circuits. The protective limits were also readjusted to accommodate operation as a rectifier.

Control Panel and Instrumentation

A new control and display panel (Figure 5-3) was added to the control console with digital readout meters to measure dc load current, dc voltage, dc power, dc converter current, ac watts, and vars. Remote controls were also added

for this demonstration. A Visicorder (multichannel oscillograph) was connected for recording the transients and a spectrum analyzer was connected for recording harmonic data.

LEGEND:

1. ON/OFF pushbutton switch — turns on inverter
2. INITIAL COND pushbutton switch — enables setting of INITIAL CONDITION potentiometer
3. DC UV INHIBIT pushbutton switch — not used
4. LEAD/LAG pushbutton switch — not used for DOE demonstration. Reverses meter readout polarity
5. INV DC AMPS digital readout — monitors inverter DC current value via system transducer
6. DC VOLTS digital readout — monitors inverter DC voltage value via system voltage divider
7. DC KW digital readout — monitors DC power (kilowatts) value derived from system control logic
8. AC KW digital readout — monitors AC power (kilowatts) value derived from system control logic
9. AC KVAR digital readout — monitors AC kilovars value derived from system control logic
10. LOAD BANK AMPS digital readout — monitors load bank DC current via system transducer
11. RECT/MAN toggle switch — in MAN position, enables POWER and VARS potentiometers to set 200 kW inversion (delivering) real power at unity PF. In RECT position, system converts to rectification mode (consumed) 200 kW real power at unity PF in 500 millisecond
12. PHASE digital readout — monitors relative phase between inverter fundamental and utility, derived from system control logic
13. NOTCH digital readout — monitors width of notch (in degrees of power pole square wave)
14. VARS 10-turn potentiometer — sets VAR output
15. POWER 10-turn potentiometer — sets kW output
16. INITIAL CONDITION 10-turn potentiometer — sets initial power condition for line parallel. Set at 30 kW for DOE demo

Figure 5-3. Control and Display Panel for Converter System

0.5-MW CONVERTER OPERATION

Manual Startup

A manual procedure was used for paralleling the system (Figure 5-4) to the utility line. The starting procedure sequence was to close the dc load bank switch, start the 0.5-MW dc supply into the load banks, and charge the bridge input filter capacitors. The capacitor charging resistors were then shorted out by a manually operated switch, and the rig started into the series reactor, harmonic-cancellation transformer, and output transformer at zero volts output. The output voltage was increased to match the utility line, and the paralleling breaker closed with the inverter-to-utility relative phase adjusted for 30-kW inversion. The system was then placed in the automatic operating mode and the desired real and reactive power demands adjusted from the control and display panel. It should be noted that the 1-MW pilot inverter does, and future inverters will, parallel the line automatically.

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Figure 5-4. Test Arrangement for 0.5-MW System

On-Line Control

The basic control consists of independent regulator/controller circuits that maintain the real and reactive powers to levels established by potentiometer settings. These regulator circuits automatically select and maintain the required relative phase angle and output voltage of the inverter bridge with respect to the line. Manual changes of these potentiometer settings were used to demonstrate operation over the real and reactive power range. Transient operation was demonstrated by manually switching from the operating point established by the real and reactive power settings to a second fixed operating point. The rate of change between the two points was controlled by a ramp function in the logic. This is analagous to a remote dispatch application.

DEMONSTRATION AND TEST RESULTS

Attendees

The Task 2 demonstration of self-commutated converter features was performed on May 26, 1977, with the following individuals in attendance:

J. Charles Smith, DOE Contract Manager
James W. Beck, EPRI
Harry Balzan, EPRI Consultant
James Birk, EPRI
Robert Snow, PSE&G
William Spindler, EPRI

Test Summary

The test was carried out in accordance with the test plan, FCR-0454, which was submitted on April 27, 1977, with the addition of a demonstration of trickle charge capability.

The 0.5-MW demonstrator test arrangement and the points of test are shown in Figure 5-4. The test sequence and data points are shown in Figure 5-5.

The features demonstrated, and their associated data points, are summarized in Table 5-1.

Figure 5-5.
Converter Data Points and
Test Sequence

TABLE 5-1. SUMMARY OF DEMONSTRATED FEATURES AND DATA POINTS

Feature	Data Point	Ac Power Delivered
Ability to operate at unity power factor without capacitors	1 8	200 kW at unity PF -200 kW at unity PF
Ability to supply vars (var control in inversion, rectification and zero power modes)	2 3 4 5 6 7	180 kW at 0.9 PF lead 180 kW at 0.9 PF lag 200 kvar at zero PF lag 200 kvar at zero PF lead -180 kW at 0.9 PF lead -180 kW at 0.9 PF lag
Ability to convert from charge to discharge mode and vice versa	10 11	200 kW to -200kW in 1/2 sec. -200 kW to +200 kW in 1/2 sec.
Cancellation of lower-order harmonics	-	Data taken at above points
Ability to operate through ac system transients	-	Data from units of the 1-MW pilot inverter used
Ability to operate in trickle charge mode	9	90 kW at unity PF

NOTES:

Lead = Deliver vars
Lag = Consume vars
+kW = Inversion or discharge mode
-kW = Rectification or charge mode

The detailed data, corresponding to the 0.5-MW system test points shown in Figure 5-4, are given in Appendix B of this report. The maximum charge and discharge rate was 200 kW, based on the limitations of the 500 kW dc power supply/200 kW dc load bank combination, which represented the energy source.

Tests and Results

Test: Ability to Operate at Unity Power Factor Without Capacitors - The 0.5-MW system was operated at the maximum charge and discharge rates, at unity power factor.

Results: The 0.5-MW system operated satisfactorily at 200 kW in both the discharge mode (data point No. 1) and the charge mode (data point No. 8) at unity power factor.

Test: Ability to Supply Vars - The system was operated at unity power factor and at maximum leading and lagging var capability for the maximum real power charge and discharge conditions. It was also operated at maximum leading and lagging var capability for an intermediate power level in both charge and discharge modes and at zero net power level. Oscilloscope traces of voltages and current were photographed for each data point. Pertinent data from the 1-MW pilot plant testing were also provided.

Results: These requirements were demonstrated by the operation at data points 1 through 8. Data for these points are presented in Appendix B. Operation was fully satisfactory, with no anomalies or instabilities observed. Data from the 1-MW pilot plant testing show the ability of the three-bridge, 1-MW pilot inverter system to operate over a complete range of var conditions at the 1-MVA level.

Test: Ability to Convert from Charge to Discharge Mode and Vice Versa - The system was operated at the maximum discharge rate and then reversed as rapidly as possible to the maximum charge rate. After a steady-state point

was established, the system was then reversed to the initial, maximum discharge point as rapidly as possible. This reversal was accomplished by changing the phase angle with respect to the line. The steady-state points between which the mode reversals take place were selected to achieve the maximum possible kVA transient with the test arrangement. During the transients ac and dc current and voltage were recorded using a Visicorder multichannel oscillograph.

Results: The 0.5-MW system was operated from 200 kW discharge (data point No. 10) to 200 kW charge (data point No. 11) and returned to 200 kW discharge (data point No. 12). Figure 5-6 is an oscillograph trace of the transition from data point No. 10 to data point No. 11. Figure 5-7 is an oscillograph trace of the transition from data point No. 11 to data point No. 12. Again, the transition was accomplished in one-half second.

Figure 5-6. Transient from 200-kW Discharge to 200-kW Charge
(Data Point 10 → Data Point 11)

Figure 5-7. Transient from 200-kW Charge to 200-kW Discharge
(Data Point 11 → Data Point 12)

Test: Cancellation of Lower-Order Harmonics - A spectrum analyzer output recording for the primary and secondary sides of the output transformer was made for each steady-state data point described above.

Results: The spectrum analyzer output was recorded for the harmonic cancellation transformer input, secondary side of the output transformer, and the primary side of the output transformer. As shown in Table 5-2, the lower-order (5th and 7th) harmonics in the two-bridge system are cancelled. Additional data with the three-bridge, 1-MW development inverter system, show harmonic cancellation to the 17th and 19th.

TABLE 5-2. CANCELLATION OF HARMONIC VOLTAGES

<u>AC Power Delivered</u>	<u>Percent of Fundamental Voltage</u>			
	Fifth		Seventh	
	HCT* Input(%)	High Side L-N(%)	HCT* Input(%)	High Side L-N(%)
200 kW, PF = 1.0	36	0	46	0
200 kvar Lead, PF = 0.0	19	0	33.5	0
200 kvar Lag, PF = 0.0	63	0	49	0
-200 kW, PF = 1.0	60	0	54	0

NOTES:

*Harmonic cancellation transformer

Lead = Deliver vars

Lag = Consume vars

+kW = Inversion or discharge mode

-kW = Rectification or charge mode

L-N = Line to neutral

Test: Ability to Operate Through AC System Transients - United has no means to initiate or control ac system transients, so no test was planned in this regard. However, normal utility switching transients do occur frequently during inverter testing. The effects of these transients on inverter operation in this test, and in other United inverter testing, will be summarized in the test report.

Results: The ability of a self-commutated converter system to operate through ac line transients has been demonstrated in 1022 hours of operation of the 1-MW pilot inverter on the 14.4-kV utility line. This experience may be summarized as follows:

- 106 voltage impulses greater than 33 percent of the nominal voltage were recorded with no inverter system interruptions, with one event greater than 150 percent of the nominal voltage.
- 33 undervoltage events (>5 percent for 1 cycle). Of these, 29 events occurred with no inverter system interruption, three events caused inverter system interruption with automatic restart when the system returned to normal, and one event occurred where the operator intervened to set the inverter system to standby.

Additional experience is available from the 0.5-MW development inverter system. A total of 169 operating hours were logged without system interruption. The 0.5-MW development converter system (in 169 hours of operation), and 1-MW pilot inverter system have demonstrated the ability to operate through the ac system transients experienced. Although this experience demonstrated the ability to handle utility system switching transients, the ability of self-commutated inverter system design to handle overcurrent surges caused by lightning strokes was not tested. However, the United inverter is designed to operate through all but the largest lightning-induced transients. Fuseblowing incidents resulting from this cause are predicted to occur less than once every two years for the worst-case Florida isokeraunic levels. (Isokeraunic level is the average annual number of thunderstorm days in a given area.)

Test: Trickle Charge - This item was added by DOE after the original test plan was submitted. The ability to provide trickle charge with continuous current and minimal ripple makes the self-commutated approach suitable for all modes of battery charging. Because the 0.5-MW system utilizes two 900-kW bridges, the system was operated at 90 kW to demonstrate a 5 percent trickle charge capability.

Results: The data taken from data point no. 9 (Figure 5-8) show that the dc current remains continuous at this condition. Additional data, taken at 5.3 kW in the rectifier mode, show the dc current is still continuous.

Figure 5-8. Trickle Charge at 90-kW (Data Point 9)

SUPPORTING DATA FROM OTHER UNITED PROGRAMS

The test plan specifies that pertinent data from the 1-MW pilot inverter system testing will be provided to demonstrate the ability to supply vars, the ability to operate through ac system transients, and the ability to cancel lower-order harmonics.

Ability to Supply Vars

The test program to demonstrate var capability is given in Figure 5-9. As shown in Figure 5-10, the test program successfully demonstrated the ability of the 1-MW system to operate over a full range of var conditions in the discharge (inversion mode).

OBJECTIVE

**DEMONSTRATE THE LEADING AND LAGGING
REACTIVE POWER DELIVERY CAPABILITY
FROM MINIMUM TO MAXIMUM POWER**

RESULTS

LEADING AND LAGGING VAR OPERATION DEMONSTRATED

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Figure 5-9. Test Program for VAR Capability

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Figure 5-10. Operating Parts Demonstrated with 1-MW Pilot Inverter System

Ability to Operate Through AC System Transients

United has no means to initiate or control ac system transients, and so the test plan specifies that experience from previous testing of the 0.5-MW development inverter system and the 1-MW pilot inverter system will be summarized to demonstrate this feature.

The 14.4-kV utility line was instrumented with a Programmed Power, Model 3250 line disturbance monitor. This unit records the following parameters to preselected levels:

- Voltage impulse: Single count for one or more positive or negative impulses with 250 millisecond minimum separation
- Under and overvoltage: Single count for each under- and over-voltage with durations of at least one 60-Hz cycle
- Frequency deviations: Single count for each under and over-frequency with durations of at least five 60-Hz cycles

The 1-MW Pilot Inverter System was operated for 1022 hours in parallel with a 14.4-kV utility line. During this period, 106 voltage impulses (exceeding 33 percent of nominal voltage) were experienced, and service was not interrupted. During the same period, 33 undervoltage events were experienced (exceeding 5 percent of nominal voltage) for at least one cycle of 60 Hz. Of these 33 events, service was uninterrupted for 29, interrupted for 3, and automatically restarted when the utility line normalized, and switched once to standby when the operator intervened.

When compared, the 0.5-MW development converter system transient experience was similar to the 1-MW Pilot Inverter System. The system operated 169 hours without service interruption.

Cancellation of Low-Order Harmonics

Figures 5-11 and 5-12 describe the test program performed on the 1-MW inverter system to demonstrate harmonic cancellation up to the 17th harmonic.

OBJECTIVE**DEMONSTRATE CAPABILITY TO DELIVER UTILITY QUALITY POWER****RESULTS****REQUIRED HARMONIC CANCELLATIONS DEMONSTRATED**

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Figure 5-11. Power Quality

Figure 5-12. 1-MW Pilot Inverter Harmonic Voltage (1-MW, 1.0 PF)

RELEVANCE TO BEST FACILITY

A general review of the high-voltage test facility, inverter testing, instrumentation, data acquisition, and recording was presented to representatives of the BEST facility prime contractor on October 21, 1976. These data, plus the detailed information provided in this report on test procedures and the characteristics and format of the test data, provide guidance to the BEST facility prime contractor in the design of a facility for the testing of advanced converters. The information describing the test of self-commutated inverter-rectifiers should provide guidance in the requirements for this type of testing.

The results of the Task 2 work have shown the need for BEST facility tests of advanced converters in the following areas:

- Advanced battery source/converter interactions - Additional testing is needed to define requirements for input filter and additional controls.
- Substation type utility interface interactions - Tests with a larger converter in a substation environment will provide additional data on the effects of utility transients.
- Operational tests with a fully automatic control system - This testing is required to identify additional requirements or modifications to present system concepts for operational use.

SECTION 6

TASK 3 – DEFINE PRELIMINARY SPECIFICATION FOR ISOLATED OPERATION

SECTION 6. TASK 3 - DEFINE PRELIMINARY SPECIFICATION FOR ISOLATED OPERATION

GENERAL TASK DEFINITIONS AND OBJECTIVES

The ability to operate isolated from the electric utility network would provide increased service reliability for the area served with an energy storage system. Additional benefits in operating cost and flexibility would be realized if inverter rectifiers used on small rural systems could respond automatically to changes in load according to some predetermined load-sharing approach. The technical requirements for such operations are not defined. The objective of this task is to define a preliminary specification for isolated operation.

SURVEY FORM AND SELECTED UTILITIES

The approach chosen to define the technical requirements for isolated operation needed to prepare a specification was to survey a combination of eight utilities and A&E firms. A survey package to guide discussions of these requirements with the individual utilities and A&E's was prepared. This package contained a cover letter and several attachments. The cover letter described the objective of the survey and provided a brief background of United Technologies fuel cell and converter activities. A description of potential applications for isolated-operation battery energy storage systems and fuel cell systems was included in the package as Attachment A. These applications were based on previous PSD studies for other programs such as EPRI's RP 114. (6) Attachment B in the survey package was a copy of the paper entitled "Inverters for Commercial Fuel Cell Power Generation." This paper, which was published in the IEEE transactions on Power Apparatus and Systems, May/June 1976, Volume PAS-95, discusses the design and design characteristics of PSD's converter.

The questionnaire portion of the survey package is Attachment C. This questionnaire was divided into four major sections. The first section, entitled "Overall," covers the potential application, principal requirements, and an assessment of the merits and features of an energy storage or fuel cell system

that has isolated-operation capability. Application characteristics including load, battery source, ac interface, and physical considerations are covered in the second section of the questionnaire. Section III is concerned with the economic factors associated with the cost of generation and the capital cost necessary to make this type of equipment attractive. The fourth and final section asks for a brief description of the overall utility system. A copy of the Attachments A and C of the survey package is incorporated as Appendix C1.

The survey-package and above-mentioned utilities to be surveyed were approved by the DOE. The utilities were selected based on suggestions by J. C. Smith, DOE Program Manager; Lowell Endahl, NRECA; and Power System Division Program Management. The list of utilities is given in Table 6-1.

The survey package was mailed and PSD followed up with a visit to each of the organizations.

TABLE 6-1. SELECTION OF UTILITIES

Utility and Contact

United Power Association
Elk River, Minnesota
Antone Rude, Assistant General Manager

Minnekota Power Cooperative
Grand Forks, North Dakota

EPRI
Ernie Ballard
(formerly with Tri-State G&T
and Nebraska Distribution System)

Santa Clara Electric Department
Santa Clara, California
Barry R. Flynn, Electrical Superintendent

Massachusetts Municipal Wholesale Electric Company
Chicopee, Massachusetts
Bruce R. McKinnon, Manager Community Power
Development

A description of these utilities follows:

- United Power Association (UPA) - UPA has a combined radial and looped distribution system at 69 kV, which serves mostly rural areas in Minnesota. It purchases most of its bulk power from North and South Dakota. The system includes an HVC ± 400 kV, ASEA-built link.
- Minnekota Power Cooperative - Minnekota is a Rural Electric Cooperative System that serves 12 distribution cooperatives. The Minnekota distribution system is primarily a looped system with some radial feeds. Future planning is directed toward backfeeding these radials with new lines to form looped networks, thus eventually eliminating the need for isolated generation during emergencies. The Minnekota system provides power to an isolated island on the Canadian border; the power requirement for this island is only 200 kW. It is the only utility in the United States that is using ripple control as part of its system's operation. The ripple control is used to control blowers and heaters in potato warehouses and heaters in water storage tanks. Being located in the part of the country that has extremely cold winters, peak-load demands last for several days to weeks.
- Santa Clara Electric Department - This is a municipal system with 100 percent purchased power serving a city of approximately 93,000 people.
- Massachusetts Municipal Wholesale Electric Cooperative (MMWEC) - MMWEC is a Joint-Action Power Supply Program and Project consisting of 29 member municipal electric systems.

Comments From Utilities

In general, the results of meetings with the utilities indicated that the ability to operate isolated from the utility grid would be of interest in the following situations:

1. For primary or energy storage power supply at the end of radial transmission systems.
2. To shave peak demand where wholesale power purchases are a major source of supply.

These contacts also indicated that development of a general specification for isolated operation since requirements are quite site specific. However, once battery systems or fuel cell systems are generally available, the use of the equipment in an isolated mode should be considered.

Survey of A&E Firms

Based on conversations with the five utilities visited, PSD felt that, in order to obtain the technical information required to prepare a specification, A&E firms would have to be surveyed. The utilities are more involved with system operations and were not in a position to generate this technical information. Three A&E firms, C.H. Guernsey & Co. (Mr. C. Massey), Oklahoma City, Oklahoma; R.W. Beck & Associates (Mr. S. Jorday), Denver, Colorado; and Burns and McConnell (Mr. Womack), Kansas City, Missouri, were contacted, were sent survey packages, and were visited.

The meetings with each of these A&E firms covered the following technical areas:

- Purpose of the survey and type of information to be obtained
- Operations of self-commutated converters in parallel with or isolated from a utility source
- Battery energy storage and fuel cell systems application
- PSD's studies for the EPRI RP114 Program

- Previous discussions with utilities contacted during the course of the survey

All firms had the same general comments and concerns about the application of a self-commutated converter system for isolated operation. These were:

- A single specification to cover all possible applications could not be written. Each installation would require systems integration work. However, a general specification describing the converter's capability for "basic" isolated operation is required to provide the guidance for preparation of the system's integration specification.
- The major technical problem to be addressed is fault-current capability to operate protection devices.
- Any additional fault-current capability that could be incorporated into the system would be of benefit for isolated mode operation.
- The amount of fault-current required would be dependent on the particular installation.
- Substation controls and protective relaying must be integrated with the converter system as a major part of the system integration.
- To complete the system's integration for some applications, modifications to existing substation and line protective equipment might be necessary.

Each of the three firms felt that it would be able to provide some technical information that would give some insight into the type of data available from firms like themselves and from utilities.

SUMMARY

The response, in the form of a completed survey questionnaire, was limited to one utility survey form and a data package from each of two A&E firms. This limited response was due to the lack of availability of the required data to complete the forms. Because of this limited response, and the opinion by all of those surveyed that a single specification could not be written, an isolated specification was not completed.

Three of the five utility types surveyed were interested in battery storage systems for isolated operation, while all five were interested in fuel cell systems. Lack of interest in the battery systems by the two utilities was because of limited storage capacity. One utility stated that battery energy storage was not attractive because their peak demands lasted several days, while the second required a carryover greater than 48 hours for emergency operation.

While the responses were very general and limited, two utilities identified fuel cell power plants operating at the end of a radial feeder for emergency operation as a possible application.

The survey of three A&E firms indicated the following technical areas of major concern:

- Fault-current capability
- Integration of substation controls and protective relaying
- Modifications to substation and line protection for integration with converter systems

The results of this survey are inconclusive with respect to the long-term requirements for isolated operation for battery energy storage systems and fuel cell systems because of the limited response. The survey indicated slightly more favorable prospects for fuel cell systems.

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