Master

# AC/DC Power Converter for Batteries and Fuel Cells

EM-662
Research Project 841-1

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## DISCLAIMER

# ABSTRACT

The overall objective of the EPRI RP841-1 program is the design of an advanced power converter for use in both battery energy storage and fuel cell generation systems in the 1980's. This goal will be accomplished by expansion of United's existing FCG-1 fuel cell power conditioning inverter into a high-efficiency inverter-rectifier system, employing improved commutation circuits and advanced (1980's) semiconductor devices, capable of operating over wider dc voltage ranges. A separate but concurrent program for the U. S. Department of Energy - (DOE) E(49-18)2122 - is examining augmentation of the present FCG-1 inverter for operation as an inverter-rectifier with battery systems; feasibility and operating characteristics have been demonstrated at this writing.

United's activities and accomplishments in the EPRI RP841-1 program include:

- Revised the preliminary specification for AC/DC Conversion Equipment contained in the Statement of Work. The dc interface specification was based on an investigation of battery characteristics in DOE E(49-18)-2122.

- Surveyed seven semiconductor manufacturers to project characteristics of 1980's thyristors.

- Screened fifteen commutation concepts (including those from EPRI RP390-1) and selected for experimental evaluation the two most promising options: Auxiliary Commutation Circuit for Surge and Controlled Commutation Energy.

- Modified existing experimental power pole hardware (previously used in EPRI RP114 and in testing United's 1 MW pilot inverter design) to evaluate the selected advanced commutation circuits; testing is now in progress.

During the remainder of the program, further analytical and experimental evaluation of the circuit concepts will be done, after which an advanced converter system approach will be chosen. Finally, a preliminary design of the selected system will be prepared, and the design verified experimentally.

# EPRI PERSPECTIVE

## PROJECT DESCRIPTION

This project is developing an AC/DC power converter preliminary design appropriate for use with battery storage. Detailed information regarding technology, its components and configuration, projected costs, technical features, limiting components, and the characteristics of components for the self-commutated type power converter are being evolved. Critical components and component configurations will be identified and laboratory tests will be conducted to verify operating features. Design and testing information will be consolidated into designs that form a sufficient base for fabrication and testing of a prototype unit.

## PROJECT OBJECTIVE

The overall objective of this project is the design of an advanced power converter system for use in both battery energy storage and fuel cell generation systems in the 1980's. This technology advancement will be beneficial to utility converters by improving full-load and part-load efficiency, reducing cost, and increasing reliability.

This annual report describes the work accomplished in the first 12 months of the project. This work was essential for analytical and experimental evaluation of advanced circuit concepts during the remainder of this project.

## CONCLUSIONS AND RECOMMENDATIONS

Seven semiconductor manufacturers surveyed to project characteristics of 1980's thyristors concluded that development of high voltage, high current inverter grade thyristors beneficial to this project's objectives will continue through the early part of the next decade.

Fifteen commutation concepts were screened and the two most promising options - auxiliary commutation circuit for surge and controlled commutation energy - were undergoing logic and hardware modifications for demonstration at the end of this report period (these options are described in this report).

The preliminary specification for AC/DC power conversion equipment for batteries and fuel cells originally contained in the statement of work has been revised to include the DC interface requirements (as of 6/77) based on an investigation of battery characteristics in DOE E (49-18)-2122.

The basic findings of this report indicate that economic and efficient self-commutated converters can be designed in the application of fuel cells and storage batteries to electric power systems.

This project's interim results strongly suggest continuation of the remaining tasks and potential realization of the overall objective.

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## SUMMARY

### PROGRAM OBJECTIVES

The primary objective of the EPRI RP841-1 program is the preliminary design of an advanced ac/dc power converter (inverter-rectifier) for use with both battery energy storage and fuel cell generation systems in the 1980's. A common converter technology, with improved characteristics, is desirable to increase market impact and hasten the introduction of these electrochemical devices into utility systems. Converters used in the battery application must operate over a wider range of dc input voltages than the fuel cell power plant. Therefore, improvements in converter technology are required to meet the cost and performance goals of a converter used in a battery energy storage system.

This project investigates, for use in battery converters, the expansion of self-commutated inverter technology being developed at United for use with its 27MW FCG-1 fuel cell power plant. The basic system design approach is to expand the FCG-1 inverter to satisfy the wider dc voltage range required for battery applications through the use of improved commutation circuits and projected 1980 semiconductor characteristics. United is investigating a second method of expanding the FCG-1 inverter technology to achieve these goals for battery converter applications through a concurrent program, U.S. Department of Energy (DOE) contract E(49-18)-2122 (Reference 1). This study will identify the most attractive modification of the basic FCG-1 inverter, such as augmentation by including an auxiliary phase-controlled rectifier or boost regulator.

RP841-1 will compare these two approaches for expanding the FCG-1 inverter design - incorporation of advanced circuits and components versus a supplemented FCG-1 inverter - and select the better design for the battery converter application. Commonality between RP841-1 and the DOE programs is ensured by comparing designs for the same dc voltage range and approximately the same power rating. RP841-1 utilizes battery characteristics determined as part of the companion DOE program.

## PROGRAM STATUS

Two principal areas of converter technology advancements are under consideration in Task 1 of this program: improvements in thyristor characteristics and improvements in commutation circuits. Technology advancement in both areas will be beneficial to utility converters by improving full-load and part-load efficiency, reducing cost, and increasing reliability.

Thyristor development has progressed at a steady pace since introduction of the device, and is expected to continue. Since the thyristor is the most important converter component, the characteristics of early 1980's devices should be incorporated into converter designs for that time frame to realize the benefits of thyristor improvements. Figure 1-1 shows several possible improvements in thyristor characteristics, and their effects on converter design. To study the trends in thyristor development, early RP841-1 efforts included a survey of thyristor manufacturers to determine the characteristics of devices which could be produced in pilot quantities by 1980.

All domestic manufacturers and two foreign manufacturers of high-powered inverter-grade thyristors were included in the survey. The results indicate that significant improvements over the 1977 "benchmark" specification of an 1800-volt, 2000-ampere rms device are anticipated. Survey responses project the availability in 1980 of thyristors with blocking voltages in excess of 3000 volts, current ratings greater than 3000 amperes rms, and turn-off times of 75 microseconds. These characteristics will be incorporated into the design of a converter using advanced commutation circuits, with a wider dc voltage range, higher power capability, and decreased cost, but without sacrificing efficiency.

- **HIGHER FORWARD BLOCKING VOLTAGE**
  - extends converter operating range to higher dc voltages without using auxiliary equipment
  - contributes to reduced snubber energy losses
  - decreases number of series SCR's required, thereby decreasing cost and energy losses
  - increases design margins, thus increasing reliability
- **REDUCED TURN-OFF TIME**
  - reduces amount of energy stored in commutation circuits, thereby reducing energy losses and cost
- **INCREASED FORWARD CURRENT**
  - greater converter power density for a given level of component stress, hence cost per KW is reduced

**Figure 1-1. Effects of Improved Thyristor Characteristics on Converter Design**

Commutation circuit design is equally important in achieving these goals of advanced converter technology. System cost and efficiency are both closely related to the size of the commutation circuit and the energy transferred by it on each cycle of operation. In addition, commutation circuit size is proportional to two factors: the peak load current to be commutated and the range of dc voltage over which the converter must operate. In the battery converter application, the wider voltage range adversely affects the cost and performance of converters using presently-available commutation circuits. Therefore, improvements to commutation circuit technology are under investigation in Task 1 of RP841-1 to assess their effects on advanced converters.

United's activity in this portion of Task 1 is directed towards examination of advanced commutation circuits, whose function is to expand the capability of the FCG-1 inverter to meet the wide dc voltage range required for battery converter operation, while meeting other program goals. The options under consideration include concepts previously identified by United, plus those investigated under the EPRI RP390-1 program (Reference 2). Each concept contributes to one or more of the design benefits shown in Figure 1-2, which will reduce converter cost, improve reliability, and allow efficient operation in an advanced battery system.

- REDUCTION IN UNWANTED INCREASE OF COMMUTATION CAPABILITY AT HIGH INPUT DC VOLTAGE
- REDUCTION IN PEAK COMMUTATION CURRENT DURING NORMAL OPERATION
- DIRECT REDUCTION OF CIRCUIT AND COMPONENT LOSSES
- INCREASED DESIGN MARGINS

Figure 1-2. Design Benefits of Advanced Commutation Circuits

Several stages of qualitative and quantitative analysis were used to screen the 15 initial commutation concepts according to their ability to meet the technical and cost criteria required for battery converter applications. Three options were selected for a more detailed final evaluation. They are listed in Figure 1-3 in the final ranking, along with the primary reasons for their selection.

FIRST: AUXILIARY COMMUTATION CIRCUIT FOR SURGE

- decreased circulating commutation energy affords improved efficiency over entire range of dc voltages
- reduced current stress main thyristor and commutation circuit
- circuit can be easily tailored to commutate different magnitudes of line disturbances
- minimum impact on cost and volume

SECOND: CONTROLLED COMMUTATION ENERGY

- separate commutation circuits can be sized and utilized for different portions of the input voltage range to give increased efficiency, especially at part load
- flexibility in selecting one of several operating schemes to best fit the application

THIRD: INDIVIDUAL COMMUTATION CIRCUIT

- lower current and voltage stress on main thyristors
- lower commutation capacitor voltages
- advanced control techniques could increase efficiency and expand voltage range capability

Figure 1-3. Three Commutation Circuits Selected for Final Evaluation

The first two circuits were selected for experimental evaluation based on higher technical ranking and similarity in design such that they could be investigated within program funding considerations. At the end of this report period, hardware from the EPRI RP-114 program (Reference 3), which was also used in testing the 1 MW pilot inverter design, has been modified for this purpose.

During Tasks 2 and 3 of this program, the predicted performance and applicability of these circuits will be investigated experimentally. An advanced system approach will be selected, based on the commutation circuit concepts evaluated in this program and the augmentation concepts selected in the concurrent DOE program. Characteristics of the selected concept will be defined to ensure that they meet design application requirements with adequate design margin. Finally, a preliminary design of the converter concept will be made and the achievable characteristics of limiting components will be defined.

## Section 2

## INTRODUCTION

### PROGRAM OBJECTIVES

The primary objective of this program is the preliminary design of an advanced ac/dc power converter (inverter-rectifier) for use with both battery energy storage systems and dispersed fuel cell generators. This design is intended to become the basis for a subsequent hardware development program; it must have a high probability for achieving the predicted technical and cost specifications. Primary emphasis is placed on meeting the requirements for operation with battery systems. The potential for operation with fuel cells is assessed and factored into the design, providing the requirements do not jeopardize operation with battery systems.

Secondary objectives of the project are to verify the converter design experimentally and to identify achievable characteristics for components which limit its performance. Consideration is also being given to the subsequent development of a prototype which can be integrated with battery system tests (in the Battery Energy Storage Test (BEST) Facility) and/or utility fuel cell demonstrations.

### PROGRAM APPROACH

EPRI RP841-1 is based on an improved bridge design for the 9 MW self-commutated inverter being developed at United for use with its 27 MW FCG-1 Fuel Cell generator. The self-commutated FCG-1 inverter system is shown in Figure 2-1. This design divides the power system into three 9-megawatt ac subsystems. In each subsystem, two 4.8-megawatt dc fuel cell modules are paralleled to feed a 9.2-megawatt inverter module. 200 kW from each module is used to supply fuel cell auxiliaries, giving a net ac output of 9 MW per module. Each module consists of three inverter bridges connected in

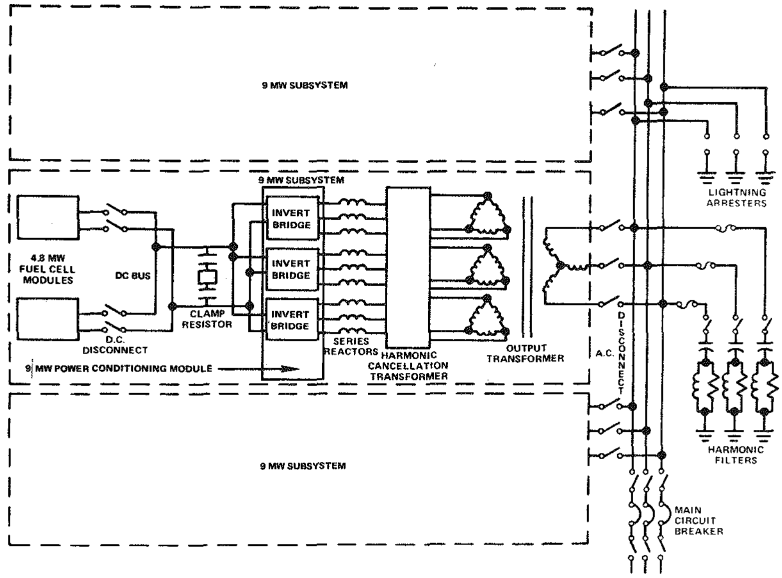


**Figure 2-1. FCG-1 27 MW Inverter System Diagram**

parallel to the input dc bus, forming an 18-pulse converter; the bridges in each power module are operated with a twenty-degree phase displacement. This arrangement permits cancellation of output voltage harmonics up to the 17th in the harmonic cancellation transformer. Reactors are inserted between the bridge outputs and the harmonic cancellation transformer to provide an inductive impedance to the utility line for control purposes and for buffering the bridge from utility line transients. If necessary, harmonic filters are provided on the high side (utility side) of the output transformer to reduce remaining harmonics. Appropriate ac and dc switchgear and fuses are provided for operational control and protective purposes. The elements of the FCG-1 self-commutated inverter system have been successfully demonstrated in the 1 MW pilot inverter system shown in Figure 2-2.

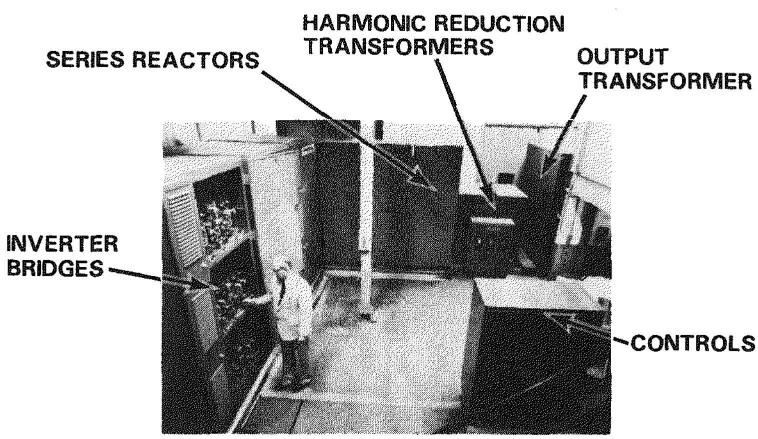


**Figure 2-2. 1 MW Fuel Cell Pilot Plant Inverter System**

Operation of a solid-state ac-dc converter in an advanced battery application requires that the converter system be operated in both charge and discharge modes (rectification and inversion) over a wide range of per-unit dc input voltages (1.6-1.7 to 1) as compared to the narrower voltage range (1.3 to 1 per unit) in the discharge-only (inversion) mode requirement of the fuel cell power plant. This wider voltage range causes increased commutation losses under certain operating conditions, thus tending to decrease converter efficiency. The wider voltage range also adversely affects converter cost. A major program goal is, therefore, the selection of an advanced commutation circuit that will reduce these additional commutation losses and allow the converter to meet its cost and efficiency goals. In addition, the program will project the improved characteristics of 1980 thyristors and assess the effect of these improvements on converter cost and performance. The converter design effort in this program will be compared with the results of a separate program, sponsored by DOE, which evaluates present-technology modifications of the FCG-1 inverter design for converter use in battery applications.

The objective of the DOE-sponsored program (E(49-18)-2122) is to evaluate United's existing self-commutated converter technology for use in the Battery Energy Storage Test (BEST) facility and related electrochemical energy storage systems. Modifications of the FCG-1 inverter were studied, including augmentation by auxiliary equipment such as a boost regulator or a phase-controlled rectifier, to meet the wider battery converter voltage range. DOE E(49-18)-2122 also successfully demonstrated self-commutated converter features, using United's 1 MW pilot fuel cell inverter. Continuation of the effort beyond the present program would lead to demonstration of advanced self-commutated inverter-rectifiers in the BEST facility.

A coordinated approach is being used to maximize the benefits from United's FCG-1 inverter design, the DOE Program E(49-18)-2122 and EPRI RP841-1. The EPRI program prepares a converter design based on FCG-1 inverter with improvements, such as advanced commutation circuits and 1980's thyristors, that will reduce or eliminate the augmentation requirement. Significant improvements are expected in converter cost and part-load efficiency compared to the reference design or results of the DOE effort. These improvements will apply to both battery and fuel cell applications. FCG-1/EPRI/DOE inter-relationships are illustrated in Figure 2-3.

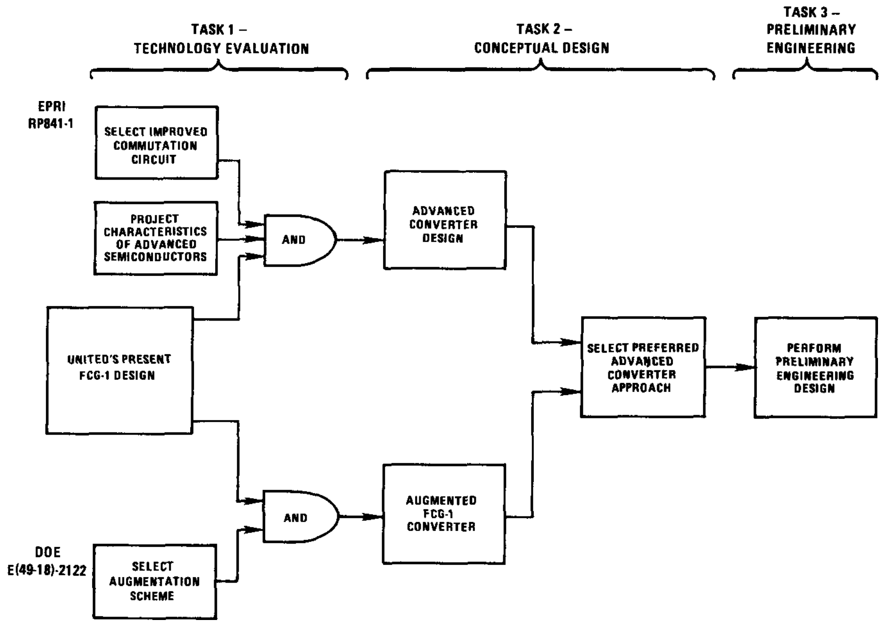


**Figure 2-3. Coordinated Program Approach and Major Features of EPRI RP841-1**

## PROGRAM STRUCTURE

The RP841-1 program is divided into three technical tasks and one program administration task. These tasks are described in the following paragraphs under appropriate headings. Figure 2-3 shows the major elements of RP841-1.

## TASK 1 - TECHNOLOGY EVALUATION

This task estimates the characteristics of converter thyristors available for demonstration purposes in 1980 and evaluates improvements to the FCG-1 commutation circuit which will provide improved efficiency and reduced cost. It is divided into three subtasks:

- Subtask 1.1 - Survey Component Manufacturers
- Subtask 1.2 - Preliminary Evaluation of Commutation Circuit Options
- Subtask 1.3 - Analytical and Experimental Evaluation of Advanced Commutation Circuits

## TASK 2 - CONCEPTUAL DESIGN AND ANALYSIS

This task selects an advanced systems approach based on commutation circuits and thyristor characteristics evaluated in Task 1 and augmentation concepts evaluated in the DOE program E(49-18)-2122. A conceptual design is prepared which meets battery and fuel cell requirements established in conjunction with EPRI's Project Manager and developed in the DOE program and in other United programs. This task is divided into three subtasks:

- Subtask 2.1 - Evaluation of Alternative Bridge Designs
- Subtask 2.2 - Conceptual Design
- Subtask 2.3 - Detailed Analysis of Conceptual Design

## TASK 3 - PRELIMINARY ENGINEERING

This task provides a preliminary experimental verification of the converter design, describes the design configuration with preliminary electrical and mechanical engineering drawings and a list of components, and defines achievable, improved characteristics for the major components which affect converter cost or performance. This task is divided into three subtasks:

- Subtask 3.1 - Design Verification
- Subtask 3.2 - Prepare Design Description
- Subtask 3.3 - Define Achievable Characteristics of the Limiting Components

The relationship of major RP841-1 milestones is given in Figure 2-4. The remainder of this document describes the individual task efforts.

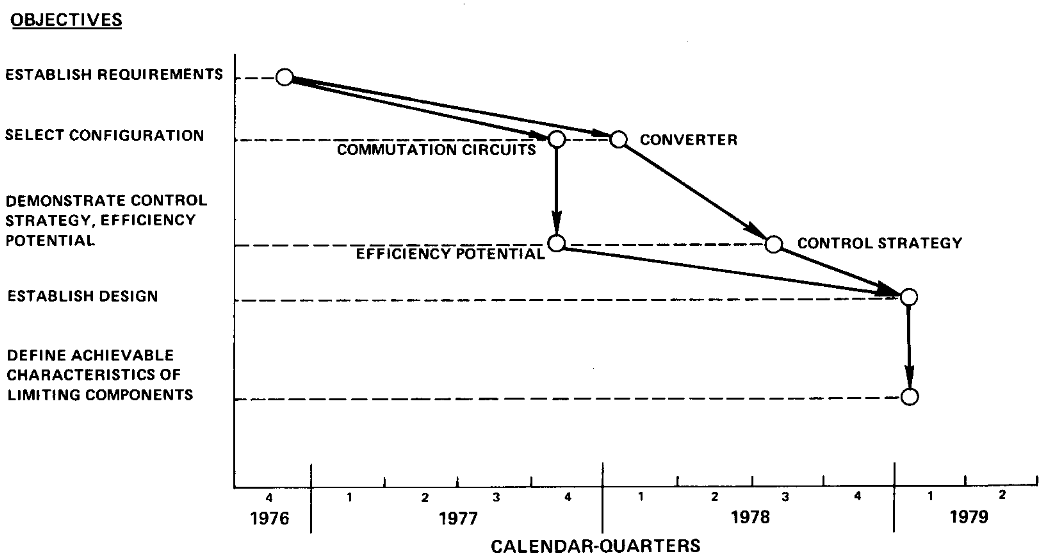


Figure 2-4. Summary of Major Milestones of EPRI RP841-1 Program

## Section 3

## TASK 1 - TECHNOLOGY EVALUATION

### GENERAL TASK DESCRIPTION

The present self-commutated inverter technology meets the requirements for United's FCG-1 fuel cell power plant and the basic needs of the converter application for batteries and fuel cells described in the contract Statement of Work. However, the wide dc voltage range encountered in the battery converter application introduces problems of cost and efficiency. This task evaluates advanced bridge circuits and components leading to a converter bridge with wider voltage-range capability, improved full- and part-load efficiency, and reduced system costs. Task 1 is divided into the following three subtasks:

- Subtask 1.1 - Survey Component Manufacturers
- Subtask 1.2 - Preliminary Evaluation of Commutation Circuit Options
- Subtask 1.3 - Analytical and Experimental Evaluation of Advanced Commutation Circuits

Subtask 1.1 is a survey of major thyristor manufacturers to identify the characteristics of thyristors which will be available for use in a demonstration converter in 1980. This subtask defines the correct technology time reference so that the components incorporated in the designs prepared in Tasks 2 and 3 are appropriate to the time frame of converter demonstration in the 1980's. Ignoring the dynamic development of the thyristor industry would distort the design analysis and result in below-optimum inverter systems. Thyristor characteristics projected for 1980 are also considered in evaluating the advanced circuit concepts of Subtask 1.2, the results of which are discussed under the appropriate heading in this section.

In Subtask 1.2, United investigated advanced commutation circuits. In theory, the ideal commutation circuit would have the ability to supply the precise amount of current to commutate the ac load regardless of the dc voltage or ac load range imposed, thereby minimizing losses. Additionally, the circuit would automatically adapt to supply sufficient additional energy to commutate increased loads of fault current when needed, and still meet cost and reliability goals. No single circuit will attain all these goals; the solution must be one of compromise between cost and performance. Trade-offs in subsequent program phases may, however, yield circuit combinations resulting in bridge conceptual designs improved beyond that which any single circuit can provide. This subtask concluded with the selection of three circuit options for further consideration. The selection process leading to identification of the promising circuit options, having those features just described, is discussed in appropriate paragraphs of this section.

Subtask 1.3 is a more intensive analytical and experimental evaluation of the selected options as well as additional promising circuits identified in other United programs. Hardware has been constructed and demonstrated; status of this evaluation is described under appropriate headings in this section.

## SUBTASK 1.1 - SURVEY OF THYRISTOR MANUFACTURERS

### Introduction

The RP841-1 program leads to a preliminary design of an ac/dc converter system in 1979 for development in the 1980-1985 time frame. Obviously, such a machine must be conceived using advanced technology components rather than today's technology. The semiconductor industry has produced a series of thyristor improvements, some of which are illustrated in Figure 3-1. The trend toward improved device characteristics is expected to continue.

| CHARACTERISTIC | 1967 | 1977 |
|---|---|---|
| CHIP DIAMETER (mm) | 33 | 63 |
| CURRENT (rms amperes) | 600 | 2000 |
| VOLTAGE (kV) | 1.2 | 1.8 |
| di/dt (amperes/$\mu$ sec) | 100 | 800 |
| dv/dt (volts/$\mu$sec) | 200 | 500 |
| RELATIVE PULSE RATING | 1.0 | 5.4 |

Figure 3-1. Progress in Characteristics of Converter Type Thyristors

Representative of previous and on-going developments in thyristor technology are:

- Amplifying-Gate Thyristor - resulting in improved high-frequency, turn-on characteristics
- Interdigitated-Gate Thyristor - resulting in improved current distribution and ratings
- Shorted-Emitter Thyristor - resulting in improved reapplied voltage characteristics
- Neutron Transmutation Doping of Silicon - resulting in more uniform doping of the wafer, which allows a higher voltage rating for a given resistivity material
- Electron-Beam Irradiation of Silicon - costing less than gold doping to control turn-off time (tq) without increased resistivity
- Larger Silicon Chips - resulting in increased current ratings and permitting greater tradeoff between voltage drop and voltage rating as a function of chip thickness
- Light Activation - resulting in improved noise immunity and reduced gate drive complexity
- Floating Chip - resulting in material cost reductions and permitting beveling both sides of the chip (multiple beveling)
- Multiple Beveling - resulting in a higher peak off-state voltage

When devices with such improved characteristics are incorporated in a self-commutated converter, there is significant impact on the design; for example:

- A higher voltage rating results in:
  - fewer devices required
  - higher efficiency
  - increased reliability
  - wider dc voltage range
  - lower voltage snubber stresses
  - reduced cost

- A higher current rating results in:
  - increased power density
  - fewer devices required
  - reduced cost

- Lower switching or conduction loss results in:
  - lower cooling demands
  - higher efficiency
  - increased reliability

- Shorter turn-off time results in:
  - improved part load efficiency
  - reduced commutation circuit requirements
  - reduced cost
  - improved transient response

- Improvement in the ability to withstand high rates of change in voltage reduces losses by reducing requirements in the device snubber circuit

Further development work is on-going in the areas of the gate-assisted turn-off switch, gate turn-off switch, light-activated switch, reverse-conducting thyristor, field-controlled switches and high power transistors in Darlington configuration.

With this background information as a prime consideration, a survey form seeking advanced technology information and projections was created. It was designed to encourage the response of leading manufacturers who had demonstrated the ability to produce high-performance, large scale semiconductors. The survey form is contained in Appendix A. In brief, the survey sought to answer the following questions:

- Where are the markets for high technology power thyristors and what is their commonality?
- What are the projected characteristics for power thyristors in the 1980's time frame?
- What are the limitations significantly impacting future thyristor development?
- What new devices can be expected?
- Where would the semiconductor industry benefit most from additional R&D support?

Seven major manufacturers were asked by United to participate in the survey. A composite summary of their responses follows under appropriate headings, each relating to sections of the survey form.

## Composite Summary of the EPRI-Sponsored High-Power Thyristor Survey

Future Applications and Markets - This portion of the survey was intended to determine the types of thyristors that would be available in the 1980's, and provide insight into their market applications (including battery energy storage). Sufficient numbers of applications with common requirements could justify higher production quantities, and lead to higher yields and lower costs per unit. In addition, emphasis trends in thyristor development were examined.

The inverter thyristors* forecast for the 1980's include chip sizes up to 77mm with ratings up to 5000 volts dc and 3000 amperes rms. Non-inverter types larger than 100mm are predicted. Device chips, 68mm in size, are presently under development by several manufacturers at levels of 1800 volts dc and 2000 amperes rms. Successful development of advanced 1980 devices depends as much on the development of sufficient high-quality material (in an appropriate size) and the development of practical advanced device manufacturing processes, as it does on the development of improved cooling, fusing, packaging and mounting techniques. Prevailing methods of pressure clamping the disc-type thyristor assemblies are not likely to suffice.

Continuing development is expected in other power semiconductors as well as basic thyristor types. Among these are gate turn-off and gate-assisted turn-off thyristors, reverse-conducting thyristors and high-power triacs (inverse-parallel thyristor pair). Historically, the development of inverter devices has lagged that of non-inverter types by a short time because inverter-grade thyristors are more complex and require more refined manufacturing and processing technology. This trend will continue.

Applications for these advanced devices are in the product areas of:

- induction heating (operating frequencies to 3 kHz)
- traction motor drives
- mining supplies
- var generators
- peaking power systems
- electrochemical refining systems
- welding
- fusion power supplies
- high-voltage direct-current power transmission (HVDC)
- uninterruptible power supplies (UPS)

Volume production quantities of 5000 thyristor devices per year are estimated for each of the following applications: traction drives, induction

*Fast switching devices for use in self-commutated converters are classified as inverter-grade devices to distinguish them from line-commutated converter devices.

heating, and UPS systems. Manufacturers estimate that annual volume production requirements of 10,000 or more of similar devices are necessary in order to provide an economical production base; the best devices are selected for the most critical applications and the remainder for less critical applications. Since quantities of thyristors in a mature dispersed fuel cell generator/ battery market (1000-2000 MW annual capacity additions) are expected to exceed 10,000 devices per year, the total requirements will be sufficient to provide an economic production base.

Thyristor development emphasis trends are shown in Table 3-1. The table indicates the relative importance which the manufacturers (A through G) place on improvement in parameters of:

- higher voltage and current ratings
- lower turn-off time (tq)
- higher yields
- lower cost

For simplicity, Table 3-1 includes an average priority weighting factor for each assessment. Higher voltage is given high priority (with one exception), followed closely by the parameters of higher current and yield. Lower tq is expected to receive the lowest priority in the near future.

TABLE 3-1. THYRISTOR PARAMETER DEVELOPMENT EMPHASIS VS MANUFACTURER

| | MANUFACTURER | | | | | | | AVERAGE STANDING OR EMPHASIS | NORMALIZED STANDING |
|---|---|---|---|---|---|---|---|---|---|
| PARAMETER | A | B | C | D | E | F | G | | |
| HIGHER VOLTAGE | 1 | 2 | 4 | 2 | 2 | 3 | 1 | 2.33 | 1 & 2 |
| HIGHER CURRENT | 2 | 3 | 3 | 1 | 3 | 2 | 4 | 2.33 | |
| LOWER tq | 5 | 1 | 5 | 5 | 4 | 4 | 2 | 4.00 | 5 |
| HIGHER YIELD | 3 | 5 | 2 | 3 | 1 | 1 | 3 | 2.50 | 3 & 4 |
| LOWER COST | 4 | 4 | 1 | 4 | 1 | 1 | 5 | 2.50 | |

Since all manufacturers are not at the same development stage for large devices, the relative emphasis displayed in Table 3-1 is expected to be influenced by the individual development lag. In general, those manufacturers that have achieved large inverter devices are now more interested in increasing yield and lowering manufacturing costs than in creating larger devices.

Improvement of Thyristor Characteristics Beyond Present Bench Mark - In this portion of the survey, manufacturers were asked to predict the improvements in thyristor characteristics for a given device that was assumed available in 1976. Figure 3-2 shows, more specifically than Table 3-1, some of the thyristor improvements anticipated by manufacturers for 1980 devices. The device characteristics (ratings) shown are forward blocking voltage ($V_{DRM}$), forward current ($I_{T(RMS)}$), and surge current ($I_{TSM}$). Device improvements are referenced to a "benchmark" thyristor, the characteristics of which are similar to those of thyristors being developed for United's electric utility program. Figure 3-2 also shows that additional improvements could be made through an accelerated development program. Figure 3-2 clearly indicates the trends toward the improved characteristics previously described. Most manufacturers noted, that within the given guidelines, several tradeoffs may be considered in parameter improvement to permit device performance to be tailored to a given application. For example, limiting VDRM to 3000 volts could result in a lower tq. Furthermore, improved VDRM and tq goals could be achieved together with advanced cooling techniques. Tradeoffs with new gate structures also offer reduced tq possibilities. The continued improvement of the thyristor characteristics indicated permits the inverter system designer a wider range of options, such as:

- Higher voltage and current ratings can reduce the need for the series connection of thyristors (or increased voltage margin) and permit fewer bridges in parallel.

- The lower component count reduces mechanical and labor costs and improves reliability.

- Lower thyristor component count tends to reduce losses because total voltage drops are reduced and fewer thyristor snubber and voltage distribution circuits are needed.

- Reduced turn-off time permits a direct reduction either in the size of commutation circuit components and commutation circuit losses, or more control flexibility via higher frequency modulation.

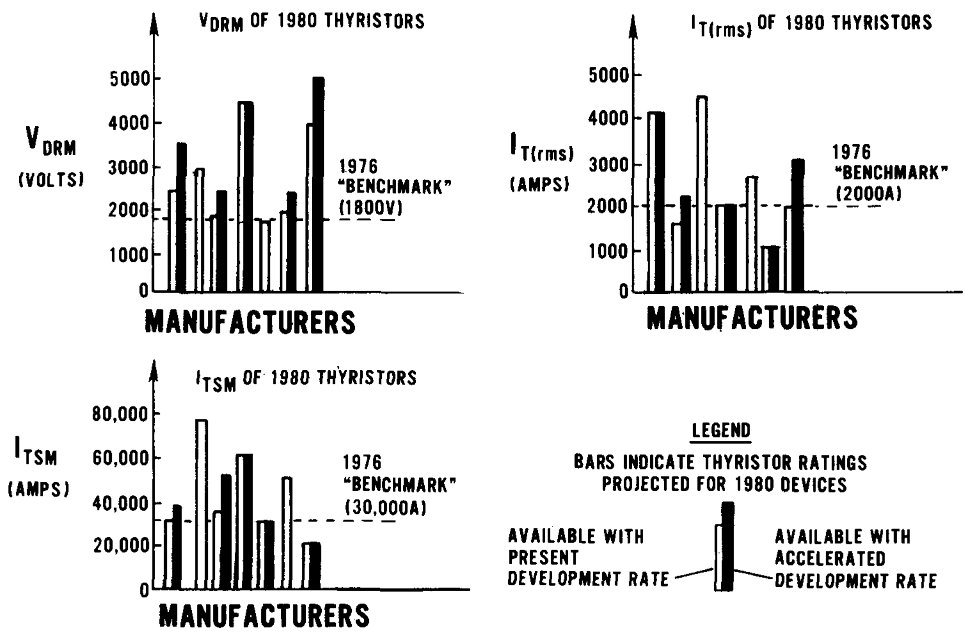


**Figure 3-2. Summary of Thyristor Manufacturer Survey Device Characteristics**

<u>Advanced Technology Materials and Semiconductor Devices</u> - Information obtained in the third portion of the survey (summarized in Table 3-2) concerns present laboratory explorations or early developmental phases for advanced devices and materials. None of the respondents foresees a semiconductor material other than silicon which could significantly improve thyristor performance. Predictions of the availability of gate-assisted turn-off devices in the sizes of interest by 1980 were mixed - ranging from an unqualified "no" to an unqualified "yes." It can be assumed that some devices will be available; however, they will not meet all the benchmark characteristics. There is unanimous agreement that light-activated, benchmark-sized thyristors will be available - possibly by 1980, or sooner. Light-activated thyristors will further reduce inverter system complexity, since gate drive circuitry will be greatly simplified and noise immunity vastly improved. When light-activated thyristors are combined with gate-assisted turn-off technology, system reliability and efficiency will be improved even further. Continuing development of higher-power, field-effect switches is expected, but not in sizes approaching the benchmark devices.

Reverse-conducting thyristors (which eliminate the discrete diode and heat sink in anti-parallel with the thyristor by combining diode and thyristor into one device) are now available with characteristics approaching the benchmark; however, their development is not being emphasized at this time because of the limited market. Benefits of this approach will be fewer heat sinks, decreased component count, and lower power pole inductance - all leading to lower costs and improved performance.

**TABLE 3-2. SURVEY RESULTS, PROJECTED DEVICE TECHNOLOGY ADVANCEMENTS**

| ADVANCED TECHNOLOGY CONCEPT | MANUFACTURERS' RESPONSES | |
|---|---|---|
| | YES | NO |
| • NEW MATERIALS | 0 | 7 |
| • GATE-ASSISTED TURN-OFF SWITCH* | 4 | 3 |
| • HIGH-POWER FIELD-EFFECT SWITCH* | 4 | 3 |
| • LIGHT-ACTIVATED GATE THYRISTOR* | 5 | 2 |
| • REVERSE-CONDUCTING THYRISTOR* | 6 | 1 |

*IN SIZES AND WITH CHARACTERISTICS REQUIRED FOR MW-SCALE CONVERTERS USED IN UTILITY DISTRIBUTION SYSTEMS.

<u>Limitation of Device Advancements</u> - The final portion of the survey identified the technology areas and other factors which influence or limit further advancement of devices.

The overall impression obtained from the survey is that continued advances in thyristor devices can be expected with development of processing techniques and gating techniques through the next decade. Expectations are for the kVA-per-device rating to increase up to four times the ratings of present-day technology (up to double existing voltage and current ratings) without additional market stimulus. This improvement will not be universal across all manufacturers unless additional sources of development funds are provided to accelerate the effort. With added development funding, a reduction in device turn-off time could be expected in the same period, resulting in a further increase in device efficiency. The reason most often given for a development lag is the relatively small demand (5000 to 10,000 devices annually) and high manufacturing costs presently identified for these large power devices. Market competition tends to depress the selling price and lowers profit margins. This results in reduced R&D expenditures.

Specific areas identified as benefiting from additional R&D support are:

- Manufacturing Methods
- Processing Equipment Development
- Packaging Technology and Techniques - includes glass passivation, lower thermal resistances, better thermal fatigue capabilities, and lower mounting forces
- Materials
- Device Technology
- Cooling
- Device Protection (fusing)

Conclusion - Subtask 1.1

In summary, the key factors derived from the survey responses are:

- Development of large (77mm) high-voltage (>2.5kV), high current (> 2000 amperes) inverter grade thyristors beneficial to the RP841-1 program objectives will continue through the early part of the next decade.
- These large devices will benefit from on-going improvements in processing techniques, as well as design improvments such as the incorporation of light-activated gate and gate-assisted turn-off structures.
- Arrival of these devices could be accelerated and their characteristics enhanced by additional R&D funding for activities resulting in better material purity and quantity, improved cooling and fuses, and improved packaging techniques.

## SUBTASK 1.2 - PRELIMINARY EVALUATION OF COMMUTATION CIRCUIT OPTIONS

### Commutation Circuit Effects on Converter Performance

The purpose of this subtask was to select analytically, from a number of previously-developed options, several advanced commutation circuits to be studied experimentally in Subtask 1.3 for applicability in the advanced converter designs.

Evaluation of commutation circuit options proceeded with the following assumptions:

- An ideal commutation circuit would have the ability to commutate the ac load regardless of the dc voltage or ac load range imposed, by providing only enough bypass current to reverse bias the thyristor for turn-off time (tq), and limit the rate-of-rise for thyristor reapplied voltage.

- The circuit would be automatically adaptable to supply sufficient additional energy to commutate increased loads or fault current when needed and still meet cost and reliability goals.

As no circuit will attain all these goals, the solution must be one of compromise between cost and performance. Tradeoffs in subsequent program phases will yield circuit combinations resulting in improved bridge conceptual designs.

Improved commutation circuits for self-commutated converters are desired to solve the problems of cost and efficiency introduced by the wide dc voltage range encountered in the battery converter application. Solutions to these problems would also benefit inverters used with fuel cell generators.

Converter cost and efficiency are both closely related to the commutation circuit design requirements and the energy transferred by the circuit on each cycle of operation. In addition, commutation circuit component requirements are proportional to two factors: the peak load current to be commutated and the range of dc voltage over which the system must operate. In the battery converter application, the wide range of dc input voltages adversely affects the cost and performance of converters using present commutation circuit designs.

Commutation circuit cost increases with voltage range because components with higher ratings are required to maintain a given stress level. Efficiency decreases because of increased commutation losses at the higher voltages. This occurs because commutation circuits use passive devices (capacitors and inductors) to store and transfer the energy required to commutate (turn off) the conducting thyristor. Losses in these components increase with the energy handled by them. Commutation circuit components must be sized to commutate maximum ac load current at minimum dc input voltage. As the dc voltage increases, the amount of energy stored and transferred by the commutation circuit during each operating cycle also increases. This increased energy is both unnecessary and undesirable, because of increased losses in the commutation circuit and because the components must be rated higher in voltage and/or current (hence more costly) to handle the increased energy. As the upper end of the dc voltage range increases, these effects become more pronounced. Therefore, improvements in commutation circuit technology are under investigation in Task 1 of RP841-1 to assess their effects on advanced converters. The major circuit improvements sought in this effort are:

- ability to operate over a wider range of input voltages
- increased part- and full-load efficiency
- reduced hardware cost
- increased system availability (reliability)

## Wide Variety of Commutation Concepts Evaluated

Six basic commutation concepts were initially selected for evaluation by United on the basis of previous inverter development experience:

- Auxiliary thyristors to provide makeup pulse
- Controlled commutation voltage
- Individual thyristor commutation circuit

- Independent commutation bus
- Improved commutation current waveshapes
- Front-end commutation

In addition, four concepts investigated by United outside the RP841-1 program were integrated into the evaluation:

- Auxiliary commutation circuit for surge
- Non-linear snubber circuit
- Control variations to reduce system losses
- Controlled commutation energy

United also considered the five self-commutated inverter circuits described in EPRI RP390-1.

All 15 concepts under initial review satisfied one or more of the technical criteria listed in Table 3-3. These criteria allow a given commutation concept to meet the program objectives, which are also listed.

TABLE 3-3. TECHNICAL CRITERIA VS PROGRAM OBJECTIVES

| TECHNICAL CRITERIA | PROGRAM OBJECTIVES |
|---|---|
| REDUCTION OF UNDESIRABLE INCREASES IN COMMUTATION CAPABILITY WITH INCREASED DC VOLTAGE | INCREASED PART-LOAD EFFICIENCY |
| REDUCTION IN PEAK COMMUTATION CURRENT FOR NORMAL OPERATION | INCREASED FULL-LOAD EFFICIENCY |
| DIRECT REDUCTION IN COMPONENT LOSSES | INCREASED EFFICIENCY OVER ENTIRE OPERATING RANGE |
| INCREASED DESIGN MARGINS | INCREASED RELIABILITY AND REDUCED HARDWARE COSTS |

The essential benefits of United's commutation concepts are described in the following paragraphs:

1. Auxiliary Thyristors to Provide Makeup Pulse - extends the input voltage range by better utilizing the main thyristors' load current capability at the low-voltage end of the range. Normal operation of the Split-C circuit requires part of the commutation current (the make-up pulse) to be conducted by the main thyristor. The addition of auxiliary thyristors removes this current from the main thyristor, allowing the main devices additional capacity for load current conduction. Thus, for constant VA (power), this could effectively decrease the low-voltage operating extreme of the inverter. Protection and coordination are also improved, since the added auxiliary thyristors can be separately fused, reducing the rms current through the main fuse.

2. Controlled Commutation Capacitor Voltage - extends range and improves part-load efficiency by controlling the losses associated with commutation current and voltage. Since commutation losses vary as the voltage, they can be held constant if capacitor voltage is maintained.

3. Individual Thyristor Commutation Circuit - reduces the input RMS current, similar to 1 above, thereby improving protective coordination and reducing input filter capacitor stresses. This circuit does not afford the same increased part-load efficiency as the primary candidates do when operated similarly.

4. Independent Commutation Bus - has an effect similar to the concept in 2 above, but its implementation is different. This method is anticipated to be more efficient.

5. Improved Commutation Current Waveshapes - limits unnecessary peak-commutation current and permits a trade-off betweeen commutation and main thyristor losses. Thus, for a fixed minimum-to-full load efficiency, the minimum voltage extreme can be decreased similar to the concept in 1.

6. Front End Commutation - can be considered in two modes:

- Normal operation concept
- Emergency switch operation concept

For normal operation, this method would require a commutation frequency six times higher than an indirect method which tends to increase losses in the commutation circuit. For abnormal operation, the circuit operates only occasionally and offers features similar to concept 7, since the normal peak commutation current can be reduced.

7. Auxiliary Commutation Circuit for Surge - extends the operating voltage range by reducing the normal commutation current. Efficiency is improved across the board and the circuit can be readily tailored to cope with different levels of line disturbances.

8. Non-linear Snubber Circuit - permits reduction of losses at high input voltage. This is achieved by reducing thyristor snubber capacitance, thereby reducing the energy discharged into the snubber resistors.

9. Controls Modifications - reduce losses and costs by using more "intelligent" controls (such as a microprocessor) to avoid some of the conditions which tend to increase component requirements, by selecting the best operating mode to match system conditions.

10. Controlled Commutation Energy - reduces operating losses by providing separate commutation circuits that are sized and selected for different operating conditions.

## Preliminary Screening Eliminates Some Concepts

As the scope of the program did not permit an in-depth evaluation of each commutation option, preliminary screening was done to initiate the selection process. This was accomplished by a qualitative review to eliminate concepts with characteristics that could prohibit their practical application, based on the following criteria:

- Relative cost
- Relative efficiency versus dc voltage range
- Circuit complexity
- Potential for further refinement

The screening process further revealed that a distinction could be made between the soft- and hard-commutation circuit approaches, as it was in the EPRI RP390-1 study. "Hard commutation" and "soft commutation" describe the two types of voltage-fed self-commutated inverters. Hard commutation is the thyristor turn-off technique that applies a high reverse voltage to the conducting device, whereas soft commutation is a technique that limits reverse voltage on the conducting thyristor during turn-off by means of an anti-parallel diode.

It was concluded that, for the same power output, a pole using hard-commutation techniques would result in more costly and "lossy" circuit elements than those used for soft commutation. Figure 3-3 gives a comparison of the most important features of the two commutation methods that lead to this conclusion. A detailed description of each technique and the rationale for identifying soft commutation as the preferred approach is provided in Appendix B.

HARD COMMUTATION

- HIGH REVERSE VOLTAGE ON THYRISTOR
- HIGH LOSS IN THYRISTOR ASSOCIATED WITH TURN-OFF
- FASTER TURN-OFF THAN SOFT COMMUTATION
- LOW DV/DT FOLLOWING TURN-OFF
- COMMUTATION THYRISTOR SUBJECTED TO HIGH DI/DT'S

SOFT COMMUTATION

- LOW REVERSE VOLTAGE ON THYRISTOR (DIODE DROP)
- VERY LOW LOSS IN THYRISTOR DURING TURN-OFF
- SLOWER TURN-OFF THAN HARD COMMUTATION
- HIGH DV/DT FOLLOWING TURN-OFF
- COMMUTATION THYRISTOR HAS LOWER DI/DT'S

**Figure 3-3. Comparison Between Hard- and Soft- Commutation Circuits**

All of the commutation concepts were screened according to the above criteria and the most promising candidates were selected. This resulted in the elimination of five concepts, which are summarized in Figure 3-4. The reasons for their elimination are discussed below.

- CONTROLLED COMMUTATION VOLTAGE
- INDEPENDENT COMMUTATION BUS
- FRONT END COMMUTATION
- NON-LINEAR SNUBBER
- IMPROVED COMMUTATION CURRENT WAVE SHAPE

**Figure 3-4. Concepts Eliminated Via Initial Screening**

The "Controlled Commutation Capacitor Voltage" concept requires large, costly iron-core magnetics. An "Independent Commutation Bus" converter requires a very low-leakage transformer; hence it was rejected because of cost. "Front End Commutation" requires insertion of inductors between the main thyristor and its anti-parallel diode for normal operation, thereby reducing commutation time; therefore, this concept was eliminated on the basis of cost and added losses. The "Non-Linear Snubber" concept was rejected because the savings in snubber losses represents only a small part of total converter losses. "Improved Commutation Current Wave Shape" was incorporated into the "Controlled Commutation" energy concept because of its similarity.

One concept, "Control Variations to Reduce System Losses," was henceforth considered a technique that could be applied to any of the other concepts. Therefore, it was no longer carried as a separate concept.

The special review of EPRI RP390-1 concepts concluded that the commutation concepts under investigation by United incorporate the best features of the Westinghouse II version favored in that report. Therefore, further evaluation of EPRI RP390-1 commutation circuits was not performed. United's comments on these circuits are summarized in Figure 3-5 and detailed in Appendix C.

- ACTRA
  - HARD COMMUTATION CIRCUIT (higher cost, lower efficiency)
  - COMMUTATING INDUCTOR MUST BE BIFILAR WOUND TO ASSURE LOW LEAKAGE. THIS CREATES INSULATION PROBLEM (cost, reliability)
- WESTINGHOUSE II
  - ARRANGEMENT OF INDUCTORS INCREASES VOLTAGE STRESS ON MAIN THYRISTORS (cost, reliability)
  - FILTER CAPACITOR BANK MUST BE SPLIT, DOUBLING NUMBER OF THESE COMPONENTS REQUIRED (cost, losses, reliability)
  - SERIES IMPEDANCE NEEDED FOR SNUBBERING OF COMMUTATION THYRISTORS (cost, losses)
- CLAMPED MC MURRAY
  - LONG TURN-AROUND TIMES LIMIT OVERLOAD CAPABILITY (performance)
  - CLAMP CIRCUIT HAS SIGNIFICANT LOSSES PARTICULARLY AT LOW POWER FACTORS
- CLAMPED SIEMENS
  - SAME COMMENTS AS CLAMPED MC MURRAY
- WESTINGHOUSE III
  - COMPLEX VERSION OF ACTRA (hence cost, performance, and reliability problems)

**Figure 3-5. Evaluation of Forced Commutated Inverters Described in RP-390-1**

Seven of United's advanced commutation concepts remained after the initial qualitative screening. These contenders were:

- Controlled Commutation Energy
- Individual Commutation Circuit
- Auxiliary Commutation Circuit for Surge
- Auxiliary SCR to Provide Makeup
- Extended Individual Commutation Circuit
- Bypass Commutation Circuit for Surge
- McMurray-Based Individual Commutation Circuit*

---

*Note: Although this is a hard-commutation version, its other benefits dictated further examination following the hard-vs-soft commutation screening.

Schematics of actual circuits that implement these commutation techniques, plus the basic "Split-C" circuit presently used, are provided in Appendix D.

## Three Final Candidates Selected

A quantitative assessment procedure was used to select from these circuits the three final candidates. This process consisted of weighing the relative merits of the contending circuits for their ability to satisfy a wide range of criteria. Figure 3-6 lists the circuits considered and their relative characteristics. The chart indicates the estimated performance characteristics, relative cost, judgement of impact on FCG-1 system design, and development time. Where the circuit option was undesirable on a cost basis, it was eliminated from further consideration.

Cost and efficiency data were estimated using a standard procedure developed by United for comparing inverter designs. This method has been verified by comparing estimated versus as-built cost and performance on large-scale hardware, such as United's 1 MW pilot fuel cell power plant. The first step was selection of components suitable for duty in converter designs employing the various commutation circuits. Each design was based on the same operating criteria: 9.6 MW dc input, 3520 to 2200 volts dc (1.6 to 1 ratio). Converter powerpole (electrical switch) efficiency was then calculated, based on the estimated commutation-only (no load) losses plus the full- or part-load losses, depending on operating point. Cost estimates were based on the extrapolation of cost data from previously-built systems, using certain physical characteristics of the components. For example, semiconductor prices were calculated from the device voltage rating and silicon chip diameter. Likewise, capacitors were priced using the capacitance and voltage rating.

From this assessment, the following circuits were judged as "final contenders": Note: Circuit Numbers refer to those listed in Figure 3-6

- Controlled Commutation Energy (Circuit 3)
- Individual Commutation Circuit (Circuit 4)
- Auxiliary Commutation Circuit for Surge (Circuit 5)

In order to evaluate the advanced converter designs (Circuits 3 to 9 in Figure 3-6) to United's FCG-1 technology, they must be compared to Circuit 2, "FCG-1 Extended Baseline," to maintain commonality of design voltage range at the 1.6-to-1 ratio. The "FCG-1 Baseline" (Circuit 1) efficiency is higher because it is only a 1.3-to-1 voltage range design.

| VOLTAGE RANGE | CIRCUIT NUMBER | PRELIMINARY ASSESSMENT CIRCUIT OPTION | EFFICIENCY (%) INVERTER MODE: FULL LOAD 9.6 MW (1) | EFFICIENCY (%) INVERTER MODE: PART LOAD (2) | EFFICIENCY (%) RECT MODE: FULL LOAD 9.6 MW (3) | ELIMINATION REASON | ELECT PARTS: ESTIMATED COST PER UNIT (4) |
|---|---|---|---|---|---|---|---|
| 3335 - 2565 | 1 | FCG-1 BASELINE (1.3 TO 1 VOLTAGE RATIO) | 98.5 | 95.1 | – | – | 1.00 |
| 3520 - 2200* | 2 | FCG-1 EXTENDED BASELINE | 98.4 | 91.5 | <97.5 | – | 1.07 |
| | 3 | CONTROLLED COMMUTATION ENERGY | 98.4 | 94.0 | 97.8 | FINAL | 1.3 |
| | 4 | INDIVIDUAL COMMUTATION CIRCUIT | 98.3 | 93.3 | 97.5 | FINAL | 1.3 |
| | 5 | AUXILIARY COMMUTATION CIRCUIT FOR SURGE | 98.6 | 94.2 | 97.8 | FINAL | 1.35 |
| | 6 | AUXILIARY SCR TO PROVIDE MAKE-UP | 98.4 | 91.8 | – | PART LOAD EFF | 1.3 |
| | 7 | EXTENDED INDIVIDUAL COMMUTATION CIRCUIT | <98.3 | <93.3 | – | COST | 1.5 |
| | 8 | BYPASS COMMUTATION CIRCUIT FOR SURGE | – | – | – | COST | 1.5 |
| | 9 | McMURRAY-BASED INDIVIDUAL COMMUTATION CIRCUIT | – | – | – | COST | 3.15 |

SEE NOTES BELOW

*1.6 VOLTAGE RATIO

LEGEND:
(shaded) = SELECTED CKT
— = NOT APPLICABLE

NOTES:

(1) THE ESTIMATED EFFICIENCY FOR ONE POLE OF A CONVERTER BRIDGE OPERATING IN THE INVERTING MODE AT 9.6 MW DC
(2) THE ESTIMATED POLE EFFICIENCY AT ¼ LOAD
(3) THE ESTIMATED POLE EFFICIENCY WHILE DELIVERING 9.6 MW DC IN THE RECTIFIER MODE
(4) THE PER-UNIT POLE ELECTRICAL PARTS COST ESTIMATE RELATIVE TO THE FCG-1 INVERTER

**Figure 3-6. Selection of Final Candidates**

"Auxiliary Commutation Circuit For Surge" Judged First Choice

Ranking of the three finalists was based on each circuit's ability to satisfy the four technical criteria (previously identified) as primary objectives of advanced commutation circuits. Evaluation was done by establishing a weighting system for comparing the circuits. This system arbitrarily assigned a score of 3 to the circuit judged to have the greatest capability for meeting each technical criterion, a 0 to the circuit having the least capability, and 1 or 2 for intermediate amounts of benefits. A subjective evaluation was then performed by a committee composed of the technical manager and his staff. During the selection process, previously determined data (used to generate Figure 3-6) was used in considering such aspects as efficiency, reliability, and relative cost.

Figure 3-7 shows the weighting system, scores, and the final ranking of the circuits. Circuit number 5 (Auxiliary Commutation for Surge) was selected as the primary candidate and circuit number 3 (Controlled Commutation Energy) as the next most attractive for further analysis in Subtask 1.2. Circuit number 5 was selected because of its overall relative advantage in reducing full- and part-load losses, and its potential for increasing design margins. Circuit number 3 also was selected for further analysis because it has similar advantages plus the potential for a more varied application with the appropriate controls development. Circuit number 4 (Individual Commutation Circuit) will be retained in an active status and reviewed periodically in light of possible changes on circuit ranking factors as the program evolves.

Figure 3-8 gives a comparison of the three selected circuits with the FCG-1 baseline and the DOE-modified (extended baseline) FCG-1. Although costs of the three advanced circuits are slightly higher than for the modified FCG-1, they show significantly better part-load efficiencies. Because of the wider range of dc input voltages in the battery converter application, the "FCG-1 Extended Baseline" and the three advanced circuits selected all show lower part-load efficiencies than the "FCG-1 Baseline." In addition, the full-load efficiency and reliability characteristics of the advanced commutation circuits are comparable to the modified FCG-1. The first two advanced circuit choices also allow greater flexibility in design of an inverter to handle different magnitudes of load current surges or transients.

| FINAL RANK ➡ | | 1st | 2nd | 3rd |
|---|---|---|---|---|
| TECHNICAL OBJECTIVES | | AUXILIARY COMMUTATION FOR SURGE | CONTROLLED COMMUTATION ENERGY | INDIVIDUAL COMMUTATION CIRCUIT |
| ● REDUCTION IN UNECESSARY COMMUTATION CAPABILITY AT PART LOAD | ———— | 2 | 3 | 0 |
| ● REDUCTION IN PEAK COMMUTATION CURRENT DURING NORMAL OPERATION | PART LOAD | 3 | 3 | 0 |
| | FULL LOAD | 2 | 0 | 0 |
| ● DIRECT REDUCTION OF LOSSES | PART LOAD | 2 | 3 | 1 |
| | FULL LOAD | 2 | 0 | 0 |
| ● INCREASED DESIGN MARGINS | AS IS | 1 | 1 | 1 |
| | POTENTIAL | 3 | 2 | 0 |
| OVERALL SCOPE | | 15 | 12 | 2 |

| BENEFIT WEIGHTING SYSTEM | |
|---|---|
| NO BENEFIT | 0 |
| MINIMUM | 1 |
| MODERATE | 2 |
| SUBSTANTIAL | 3 |

**Figure 3-7. Ranking of Final Candidates Based on Technical Objectives**

| VOLTAGE RANGE | CIRCUIT NUMBER | PRELIMINARY ASSESSMENT CIRCUIT OPTION | EFFICIENCY (%) INVERTER MODE: FULL LOAD 9.6 MW (1) | EFFICIENCY (%) INVERTER MODE: PART LOAD (2) | EFFICIENCY (%) RECT. MODE: FULL LOAD 9.6 MW (3) | ELIMINATION REASON | ELECT. PARTS: ESTIMATED COST PER UNIT (4) | IMPACT ON FCG-1 SYSTEM DESIGN: BRIDGE | IMPACT ON FCG-1 SYSTEM DESIGN: OVERALL SYSTEM | DEVELOPMENT TIME: MONTHS |
|---|---|---|---|---|---|---|---|---|---|---|
| 3335 – 2565 | 1 | FCG-1 BASELINE | 98.5 | 95.1 | – | – | 1.00 | – | – | – |
| | | (1.3 TO 1 VOLTAGE RATIO) | | | | | | | | |
| 3520 – 2200* | 2 | FCG-1 EXTENDED BASELINE (DOE) | 98.4 | 91.5 | <97.5 | – | 1.07 | – | – | 3-6 |
| | | FINAL CONTENDERS | | | | | | | | |
| | 3 | CONTROLLED | | | SECOND CHOICE | | | | | |
| | | COMMUTATION ENERGY | 98.4 | 94.0 | 97.8 | FINAL | 1.3 | ◆ | ◇ | 6-9 |
| | 4 | INDIVIDUAL | | | THIRD CHOICE | | | | | |
| | | COMMUTATION CIRCUIT | 98.3 | 93.3 | 97.5 | FINAL | 1.3 | ◆ | ◇ | 6-9 |
| | 5 | AUXILIARY COMMUTATION | | | FIRST CHOICE | | | | | |
| | | CIRCUIT FOR SURGE | 98.6 | 94.2 | 97.8 | FINAL | 1.35 | ◆ | ◇ | 3-6 |

SEE NOTES BELOW

*1.6 TO 1 VOLTAGE RATIO

NOTES:

(1) THE ESTIMATED EFFICIENCY FOR ONE POLE OF A CONVERTER BRIDGE OPERATING IN THE INVERTING MODE AT 9.6 MW DC
(2) THE ESTIMATED POLE EFFICIENCY AT ¼ LOAD
(3) THE ESTIMATED POLE EFFICIENCY WHILE DELIVERING 9.6 MW DC IN THE RECTIFIER MODE
(4) THE PER-UNIT POLE ELECTRICAL PARTS COST ESTIMATE RELATIVE TO THE FCG-1 INVERTER

LEGEND:

░ = SELECTED CKT
◇ = MINOR
◆ = MAJOR
— = NOT APPLICABLE

**Figure 3-8. Final Evaluation Summary and Comparison to Modified DOE FCG-1 Inverter**

Various other technical factors of the three selected circuits are shown in Figure 3-9. These also aided in the qualitative review and evaluation procedure.

| FACTOR | AUX. COMM. FOR SURGE | CONTROLLED COMM. ENERGY | INDIVIDUAL COMM. CIRCUIT |
|---|---|---|---|
| · OPERATING FEATURES | SOMEWHAT BETTER MARGINS DURING NORMAL OPERATION. | 1. CAN OFFER LOWER PART LOAD LOSS IF SPLIT-C COMM. CAPS SIZED FOR 100% LOAD AND SUPPLEMENTAL COMM CIRCUIT SIZED FOR PART LOAD.<br>2. MORE SOPHISTICATED SWITCHING PATTERN (CONTROLS) CAN PROVIDE PEAK COMM CURRENT WAVE SHAPE CONTROL. | 1. SOMEWHAT BETTER CURRENT MARGIN THAN FCG-1 SINCE THE MAIN DEVICES DON'T CARRY THE COMM CURRENT.<br>2. PART LOAD EFFICIENCY CAN BE IMPROVED BY MODIFICATIONS THAT ALSO ALLOW CIRCUIT TO TOLERATE LARGER VOLTAGE RANGES |
| · PROTECTION AND FUSE COORDINATION | EASIER FUSE COORDINATION DUE TO REDUCTION OF THE CIRCULATING BUS CURRENTS. | THE ADDITIONAL COMM CIRCUIT WITH A DIFFERENT RATING FROM THE FIRST, MAY BE A MORE DIFFICULT PROTECTION PROBLEM THAN IS A SINGLE CIRCUIT (AS IN FCG-1). THIS IS PROBABLY NOT A MAJOR FACTOR. | THE MAIN DEVICES SEE A LOWER VOLTAGE THAN IN THE SPLIT-C CIRCUIT BUT THE AUXILIARY DEVICES SEE ABOUT TWICE THE SPLIT-C VOLTAGE. THE COMM CAP VOLTAGE DOES NOT EXCEED THE DC BUS VOLTAGE AS IN THE SPLIT-C. AUXILIARY DEVICES NEED SEPARATE FUSING. |
| · SIZE AND VOLUME | MINIMAL IMPACT ON VOLUME COMPARED TO BASELINE SPLIT-C. | LARGER THAN FCG-1 SPLIT-C. | LARGER THAN FCG-1 SPLIT-C. |
| · ABILITY TO HANDLE SURGES | CAN BE CUSTOM DESIGNED FOR THE APPLICATION. | CAN BE MADE GREATER THAN THE EXTENDED RANGE FCG-1 BY USING A LARGER TOTAL CAPACITANCE THAN IN THE FCG-1. | SAME AS IN FCG-1. |
| · RECTIFIER MODE OF OPERATION | SAME AS BASELINE SPLIT-C. | SAME AS BASELINE SPLIT-C. | SLIGHTLY BETTER THAN FCG-1 SPLIT-C SINCE THE MAIN THYRISTOR DOESN'T CARRY THE COMM PULSE. |
| · SHOOT THROUGH | SAME AS BASELINE FCG-1; ONLY ONE SHOOT THROUGH PATH. | SAME AS FCG-1; ONLY ONE SHOOT THROUGH PATH. | WORSE THAN FCG-1; FOUR SHOOT THROUGH PATHS. |
| · IMPACT ON INPUT FILTER | 1. DC BUS CURRENTS ARE HIGHER DURING THE SURGE COMMUTATION BUT THIS IS NOT A PROBLEM.<br>2. NORMAL CIRCULATING COMM CURRENTS ARE LOWER THAN THE BASELINE SPLIT-C. | LOWER PEAK COMM CURRENT, AND THEREFORE, LOWER FILTER LOSSES THAN EXTENDED FCG-1. | ELIMINATES THE CIRCULATION OF COMMUTATION CURRENTS IN THE INPUT FILTER AND BUS WORK; THEREFORE, FILTER AND BUS LOSSES ARE REDUCED AND HIGHER IMPEDANCE BUS WORK MAY BE USED. |
| TURN AROUND TIME | LONGER DURING THE SURGE COMMUTATION CYCLE THAN DURING THE NORMAL CYCLE. THIS IS NOT A PROBLEM. | SAME AS FCG-1. | TURN AROUND TIME IS ALWAYS MAXIMUM. |

**Figure 3-9. Technical Factors Affecting Circuit Choice**

The major features of the first choice, Auxiliary Commutation Circuit for Surge, are summarized as follows:

- Decreased circulating commutation energy affords improved efficiency
- Low duty of auxiliary circuit permits use of lower performance components
- Inherent flexibility to design in different amounts of commutation capability

- Reduced current stress in main thyristor, commutation thyristor and input filter capacitor

- Small cost increase

- Minimum impact on volume

- Reliability as good as FCG-1

## SUBTASK 1.3 - ANALYTICAL AND EXPERIMENTAL EVALUATION OF ADVANCED COMMUTATION CIRCUITS

### Objectives

Two of the three circuits selected in the previous subtask as "final contenders" were chosen for further analysis in this subtask; they are: Auxiliary Commutation Circuit for Surge and Controlled Commutation Energy.

The Auxiliary Commutation Circuit for Surge consists of a basic Split-C circuit plus an auxiliary circuit, as shown in Figure 3-10. The principle of operation uses the basic Split-C circuit to provide for normal loads, and activates an auxiliary circuit to provide the additional commutation energy required for abnormal conditions, such as switching and lightning surges.

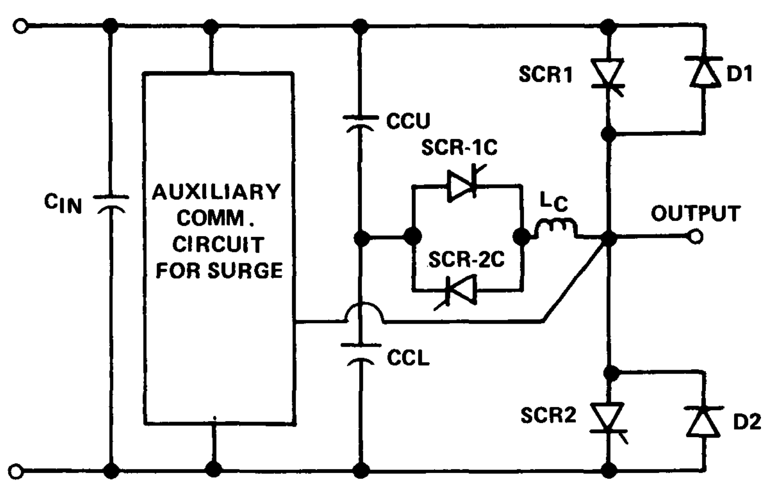


**Figure 3-10. Auxiliary Commutation for Surge, 800-Amp Normal, 1300-Amp Surge**

The Controlled Commutation Energy Circuit consists of a basic Split-C circuit plus a supplemental commutation circuit, as shown in Figure 3-11. While there are several ways to combine the operation of these circuits to minimize the commutation losses, the initial concept investigated was the use of the basic Split-C circuit for the high end of the dc voltage operating range (including light-load operation), while the supplemental circuit was used for the lower end of the dc voltage operating range (including overload).

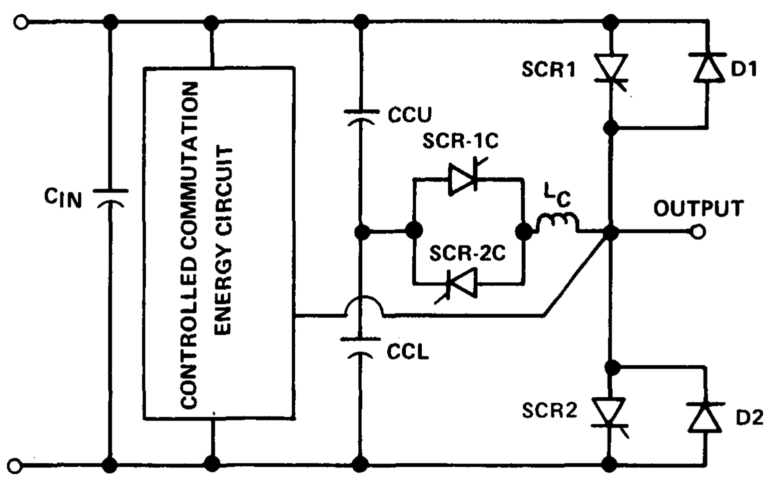


Figure 3-11. Controlled Commutation Energy, 800- or 1300-Amp

Experimental evaluation of these circuits which had previously been reduced to practice was performed to meet the following objectives:

- verify circuit operating principles
- provide experimental data for sizing components of an optimized system
- substantiate and refine computer simulation models

The experimental program was designed to utilize United's existing megawatt-scale, Split-C powerpole equipment which was previously used in the EPRI RP114 program and in testing of the 1 MW pilot inverter. Because the hardware modifications incorporated to represent the advanced circuits were principally intended to examine their feasibility and major operating characteristics, the circuits' performance were not optimal compared to a system specifically designed for the application. In addition, this experiment was a single-pole demonstration of the concepts, and therefore, neglected the effects of load. However, the experimental results will be projected using computer simulation techniques to study some of the conditions not run in the laboratory.

In order to satisfy the battery voltage range of 1.7:1 that corresponds to the 7-hour charge and 5-hour or 10-hour discharge cycles projected for advanced battery systems, the tests are run over the voltage range of 1750 to 1030 volts dc. The most important parameters examined were:

- practical limitations relative to the baseline Split-C
- commutation capability relative to the baseline Split-C
- commutation losses relative to the baseline Split-C

## Test Plan

Experimental evaluations of the advanced commutation circuit options will be performed according to the following test plan:

1. The hardware is set up as a "baseline" Split-C powerpole (see Figure 3-12) capable of commutating 800 amperes peak load current. This pole is operated over the range of 1750 to 1030 volts dc (1.7:1) to obtain reference data, including commutation current, capacitor voltages, and tare power at discrete operating voltages. No-load power (tare) is a measure of commutation loss.

2. The hardware is reconfigured as a Split-C pole capable of commutating 1300 amperes peak load current, and a new set of reference data is taken.

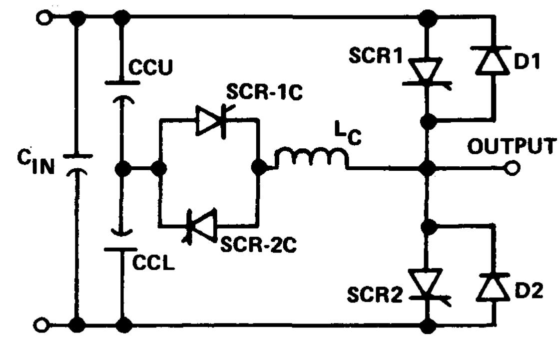


**Figure 3-12.** **Baseline Reference Split-C Pole, 800- or 1300-Amp Commutation Capability**

3. Modifications are made to the baseline Split-C, returning it to 800 ampere load current commutation capability and incorporating the Auxiliary Circuit for Surge (see Schematic, Figure 3-10) providing a combined surge commutation capability of 1300 amperes peak load current. This pole is operated at the same dc voltages as the baseline pole (except at the highest end of the range because of component limitations in the auxiliary circuit solid-state switches). Performance is verified and data is recorded for comparison with the reference data.

4. The hardware is again modified to demonstrate the Controlled Commutation Energy circuit (see schematic Figure 3-11). This is done by connecting to the first 800-ampere Split-C pole the commutation circuit of a second baseline-style pole rated 1300 amperes load current. Again, the pole is operated over the 1.7:1 dc voltage range to confirm proper circuit operation and obtain commutation energy and loss data for comparison with the baseline pole.

## Hardware Modifications

All of the experimental evaluation is accomplished by modifying existing powerpole hardware and control logic. The logic modification allows the controls to be used for both the Auxiliary Commutation Circuit for Surge and the Controlled Commutation Energy circuit. Required modifications for implementing each of the two advanced commutation circuits are described below, and photos are provided in Figures 3-13 and 3-14.

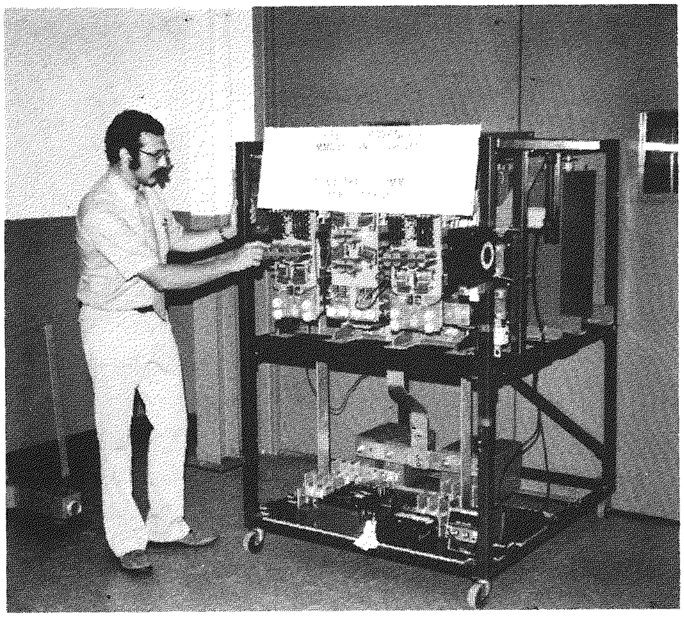

Figure 3-13. Experimental Auxiliary Commutation Circuit for Surge

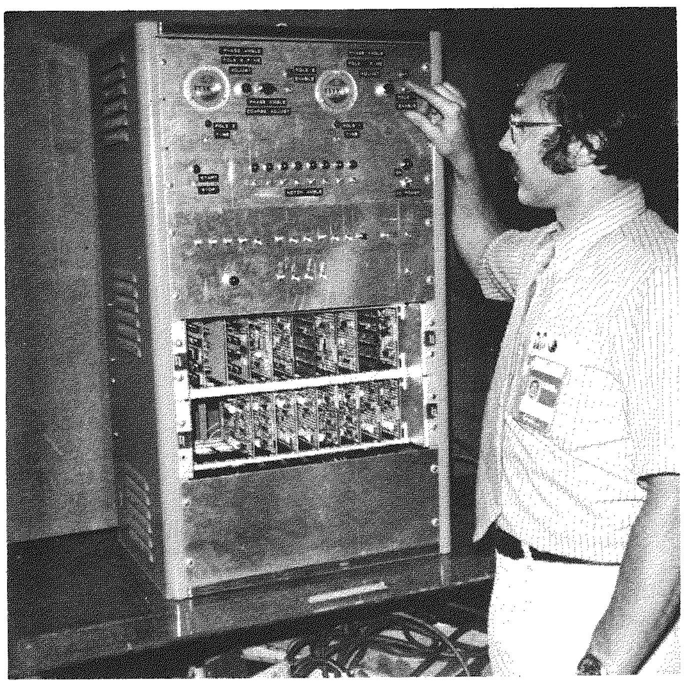

Figure 3-14. Power Pole Control Logic

Auxiliary Commutation Circuit for Surge

One experimental Split-C powerpole was used with auxiliary commutation circuit components mounted below the pole and connected with short lengths of bus bar. Heatsinks were not required for the auxiliary semiconductors because of the low duty cycle. Minimum snubbers were required on auxiliary devices because the dv/dt is limited to very low values compared to device ratings. The control logic operates in normal Split-C mode unless operator manually initiates "surge" commutation. Control logic switches in auxiliary circuit and changes thyristor gating pattern of Split-C circuit for selected number of subsequent commutations to provide for longer time constant when auxiliary circuit is switched in, then returns to normal.

Controlled Commutation Energy

Two experimental Split-C powerpoles were used with one contributing only its commutation circuit. Short runs of bus bar were used to connect the two poles. The control logic was modified to allow running the basic Split-C powerpole either manually or automatically, transferring to the supplemental commutation circuit and back again.

Summary

At the end of this report period, required logic and pole hardware modifications had been made for demonstration of both advanced commutation circuits. Instrumentation was installed to measure the following parameters:

- input dc voltage
- input dc current
- commutation current waveforms
- capacitor voltage waveforms
- thyristor voltage waveforms

Data will be taken according to the test plan, then used for further evaluation of the circuits. Part of this evaluation will include use of the experimental results to refine the Advanced Statistical and Transient

Analysis Program (ASTAP)* computer simulation model. Simulation techniques will then be used for analysis of additional operating conditions to study load and transient effects.

*ASTAP is an IBM standard package circuit analysis program.

## Section 4

## TASK 2 - CONCEPTUAL DESIGN AND ANALYSIS

### INTRODUCTION

The primary objectives of this task are to:

- review the preliminary specification of the Attachment A in the RP 841-1 Statement of Work and recommend revised requirements where appropriate

- evaluate alternative advanced bridge designs derived from the advanced commutation circuit options of Task 1

- produce a conceptual design for the ac/dc converter system which conforms to the electrical requirements for battery and fuel cells as established by the RP841-1 Attachment A, as well as by the concurrent DOE program E(49-18)-2122

- perform a detailed analysis of the conceptual design to ensure that it meets application requirements with adequate design margin

The analysis includes subsystem elements such as the powerpole, magnetic components, controls concept, etc. Failure mode and effect analysis is combined with simulation to predict availability and performance. The mechanical design and its evaluation will be based upon United's FCG-1 inverter design.

### STATUS

To date, the first objective milestone has been met, the second subtask is on-going, and the remaining are not scheduled until later in the program. The revised RP841-1 Attachment A, incorporating United's recommendations, is contained in Appendix E. This preliminary specification will serve as a guideline in preparing the converter conceptual design in this task, and for the preliminary engineering of Task 3.

United's recommendations were presented to EPRI representatives at the second program oral review on April 27, 1977. Revisions have been included which incorporate EPRI's directions to United at that review. Those items which are different (revised) from the original Attachment A are shown with a bar in the right hand margin.

The elements of the RP841-1 Attachment A are separated into three basic parts:

- General Considerations
- Electrical Considerations
- Protection and Protection Coordination

General Considerations includes such things as environmental, maintenance, and safety features. Electrical Considerations includes both dc and ac interfaces and operating requirements. Protection and Protection Coordination is 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 concurrent DOE program E(49-18)-2122 provided the required definition of the dc source.

A rationale for major changes in the specification from United's FCG-1 program for those areas not previously considered is discussed below in the order of appearance in Attachment A, Appendix E.

## Power Rating Base

This factor has been reviewed by EPRI in RP390-1 as well as in other reports. 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 this 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 $/kW can change even though the total capital expense does not change. United has recommended (and EPRI has agreed) that the peak deliverable power at start of discharge is the most reasonable and meaningful point for defining the system rating to the utility.

## DC Voltage Range

For fuel cells, the listed factor is obtained from the FCG-1 program. The 2200 vdc minimum voltage is consistent with United's fuel cell program and with EPRI's directive to provide a preliminary design suitable for both battery and fuel cell operation. For batteries, the studies of advanced battery cell characteristics performed in DOE program E(49-18)-2122 provided the definition. Those advanced battery cell studies were conducted by surveying battery manufacturers and analyzing their responses.

A survey form was prepared to acquire the battery characteristic information necessary to define the battery/inverter-rectifier interface. This form was then forwarded by DOE and EPRI to six advanced battery developers. The form was designed to elicit 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. Completed survey forms, returned by the developers, were followed by telephone conversations in cases where additional information was required.

In addition, visits were made by PSD personnel to Bechtel, EPRI, and Argonne National Labs. PSD representatives participated in the First Annual DOE Battery Contractors Coordination Meeting, January 27-28, 1977; the BEST Facility Workship II February 10, 1977; and, the Lead Acid Battery Workshop December 9-10, 1976.

Information was obtained on the following types of advanced batteries:

- Sodium - Sulphur (2 developers--hence designations "type 1" and "type 2")
- Sodium - Antimony Trichloride
- Zinc - Chlorine
- Lithium/Metal Sulphide (2 developers - hence designations "type 1" and "type 2")

Information available at the program inception, as well as the EPRI RP841-1 Statement of Work, directed 10-hour discharge cycles. Subsequent discussions with the advanced battery developers who responded to the survey, as well as information contained in the EPRI-EM-264/DOE E(11-1)-2501 Energy Storage Systems report, indicated that 5-hour discharge rates are also of importance. The 5-hour rate would approximately double the number of applications for battery energy storage, as well as being more cost competitive with alternate generating methods at the 5-hour rate. Accordingly, the 5-hour discharge criterion is considered in all subsequent work. It is important to note that for both the 10-hour and 5-hour discharge rates, that 1.3:1 voltage ratio from start-of-discharge is compatible with the fuel cell generator application voltage ratio of 1.3:1 between minimum rated load at beginning-of-life and maximum rated load at end-of-life.

For the 7-hour charge and 10-hour discharge baseline cycle, the battery characteristics may be summarized as follows:

- A maximum voltage ratio for end-of-discharge of 1.6:1 satisfies all batteries surveyed except the Li/metal sulphide - type, which has a voltage ratio of 2.06:1

- A maximum voltage ratio for start-of-discharge to end-of-discharge of 1.35:1 satisfies all batteries surveyed except the Li/metal sulphide - type 1, which has a ratio of 1.7:1. The 1.35:1 voltage ratio of the Sodium-Antimony Tricholoride can be reduced to 1.30:1 with a slight shortening of the discharge time. This has a negligible effect on the available energy

- Energy efficiencies were estimated from either the duty-cycle profile curves or the product of voltage and ampere-hour efficiencies. For the 10-hour discharge rate, 85% efficiency is a realistic assumption for the battery only

For the 7-hour charge and 5-hour discharge cycle, the battery characteristics may be summarized as follows:

- A maximum voltage ratio for end-of-charge to end-of-discharge of 1.7:1 satisfied all the batteries surveyed except the Li/metal sulphide - type 1, which has a ratio of 2.4:1

- A maximum voltage ratio for start-of-discharge to end-of-discharge of 1.3:1 satisfies all the batteries surveyed except the Li/metal sulfide - type 1, which has a ratio of 1.8:1 (estimated)

- For the 5-hour dischage, 80% battery energy efficiency is a realistic assumption

For the 7-hour charge and 3-hour discharge cycle, the battery characteristics may be summarized as follows:

- Maximum voltage ratio for end-of-charge to end-of-discharge of 1.9:1 satisfies all the batteries surveyed except the Li/metal sulfide - type 1, which has a ratio of 2.8:1

- A maximum voltage ratio for start-of-discharge to end-of-discharge of 1.5:1 satisfied all the batteries surveyed except the Li/metal sulfide - type 1, which has a ratio of 1.7:1 (estimated)

- For the 3-hour discharge, 70% battery energy efficiency is a realistic assumption

The changes to the dc voltage range recommended by United reflect the cell performance characteristic just described.

## Power Rating

The nominal converter system rating of 27MW ac at unity power factor is derived from the FCG-1 fuel cell inverter system rating and is consistent with EPRI's directive to provide a preliminary design suitable for both batteries and fuel cells. Consideration will be given to modification of this criterion if advantageous.

## Harmonics

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.

United's recommendations for the remaining items of Appendix E reflect factors previously considered and defined in the FCG-1 program. These guidelines will be incorporated into the conceptual design and analysis and preliminary engineering phases of this project. Certain portions of the preliminary specification may be subject to revision prior to the construction of actual converter hardware.

## Section 5

## TASK 3 - PRELIMINARY ENGINEERING

### GENERAL

Work on Task 3 is not scheduled until January 1, 1978. No work performed during this reporting period.

Section 6

## REFERENCES


(1) "Evaluation of Inverter-Rectifiers Based on FCG-1 Inverter Systems", DOE Contract E(49-18)-2122, September 7, 1976, Power Systems Division of United Technologies Corporation.

(2) "AC/DC Power Conditioning and Control Equipment for Advanced Conversion and Storage Technology," EPRI Research Project 390-1, Final Report, July, 1975, Westinghouse Electric Corporation.

(3) "Advanced Technology Fuel Cell Program," EPRI Research Project 114-1 Final Report No. EM-335, October, 1976, Power Systems Division of United Technologies Corporation.

## APPENDIX A

HIGH POWER THYRISTOR SURVEY

# HIGH POWER THYRISTOR SURVEY

## A. FUTURE APPLICATIONS AND MARKETS

Please comment on present trends for high voltage ( > 1800 volts) and high current ( > 1500 amps) average thyristors.

1. What types of devices will be available?

2. What do you see as the application for these devices in 1980?

3. Do any of these have volume potential? If so which?

4. Please arrange the following in order of priority with respect to present development emphasis from highest to lowest.

Higher Voltage ____________________

Higher Current ____________________

Lower Turn - off time ____________________

Higher Yield ____________________

Lower Cost ____________________

B. IMPROVEMENT OF THYRISTOR CHARACTERISTICS BEYOND PRESENT BENCH MARK

Assuming the bench mark thyristor (listed below) is available in 1976, what improvements to device characteristics do you foresee in 1980, (1) at your present development rate and (2) at an accelerated development rate?

Please specify levels of improvement for each characteristic you feel is attainable without significant sacrifice to any of the others listed.

| 1976 THYRISTOR | 1980 THYRISTORS | |
|---|---|---|
| Bench Mark | Available at Present development rate | Available at an accelerated development rate |
| 1. $V_{DRM} \geq 1800$ volts ($V_{DRM} = 100$) | | |
| 2. $I_T$ (RMS) $\geq$ 2000 Amps | | |
| 3. $I_{TSM} \geq$ 30,000 Amps | | |
| 4. $V_{TM}$ at 25°C, 3000 Amps PK $\leq$ 1.5 Volts | | |
| 5. $T_q \leq$ 75 Microseconds | | |
| a. With reverse diode | | |
| b. With $\geq$ 500V/usec reapplied dv/dt | | |
| c. With $T_J \geq$ 125°C | | |
| 6. di/dt = 250 Amps/usec (repetitive) | | |

7. Please comment on possible parameter trade-offs (e.g., faster turn-off at expense of $V_{DRM}$) factors that will allow the improvements.

C. ADVANCED TECHNOLOGY MATERIALS AND SEMICONDUCTOR DEVICES

Please comment on the impact of the following advanced technologies for commercially available semiconductor switches.

1a. Is there a semiconductor material other than silicon which could significantly impact the performance of thyristors?

b. If such a material has been identified, when would you expect high production capability?

2. Would you expect semiconductor devices such as the gate-assisted turn-off switch to be technically feasible in the sizes indicated by the bench mark thyristor (B)?

   If yes, when?

3. Do you foresee high-power field-effect switch availability in the 1980's?

4. When do you expect a totally light activated gate thyristor of the size of interest to be available?

5. When do you expect a reverse conducting thyristor of the sizes of interest to be available?

D. LIMITATIONS OF DEVICE ADVANCEMENTS

Please comment on the primary factors influencing the development of higher performance semiconductor switches.

1. In what area of technology would the semiconductor industry most benefit from additional R & D support. (such as semiconductor material, device technology, processing development etc)?

2. What do you consider the greatest limitation for device advancements?

# APPENDIX B

## COMPARISON OF COMMUTATION COMPONENT SIZE REQUIREMENTS FOR HARD AND SOFT COMMUTATION

During the course of the commutation circuit option screening process, a comparison was made of the cost of the candidates. As part of that process, circuits using hard-commutation versus soft-commutation thyristor turnoff techniques were separated into distinct categories.

This document presents examples which demonstrate the principle that for the same operating conditions, hard-commutation circuit components tend to be larger, and hence more costly and more "lossy," than their soft-commutation counterparts.

MINIMUM LOAD EXAMPLE

Figures 1A and 1B show soft- and hard-commutation circuits, respectively. To function properly, each circuit must be designed to remove the conduction current from the main device M, for the thyristor's turnoff time ($t_q$). Turnoff time is assumed to be the same for both circuit types. In practice, however, soft-commutated thyristors exhibit somewhat longer turnoff times.

Figure 1C shows the current through the commutation capacitor (C) for both circuits with switch S closed, assuming that each circuit has the same half-cycle period, $t_p = \pi \sqrt{LC}$ and peak current,

$$I_C = \frac{E_{C_o}}{\sqrt{L/C}}$$

Load current is presumed to be small enough to be negligible on the scale of the figure. Thus, during the entire time $t_p$, the available commutation current exceeds load current, permitting device M to recover its blocking capabilities.

Figure 1D shows the voltage across the device M during this period $t_p$, for the soft commutation circuit. Because of commutation current flow through diode D, the thyristor is reverse biased with a voltage equal to the diode drop for the full time $t_p$.

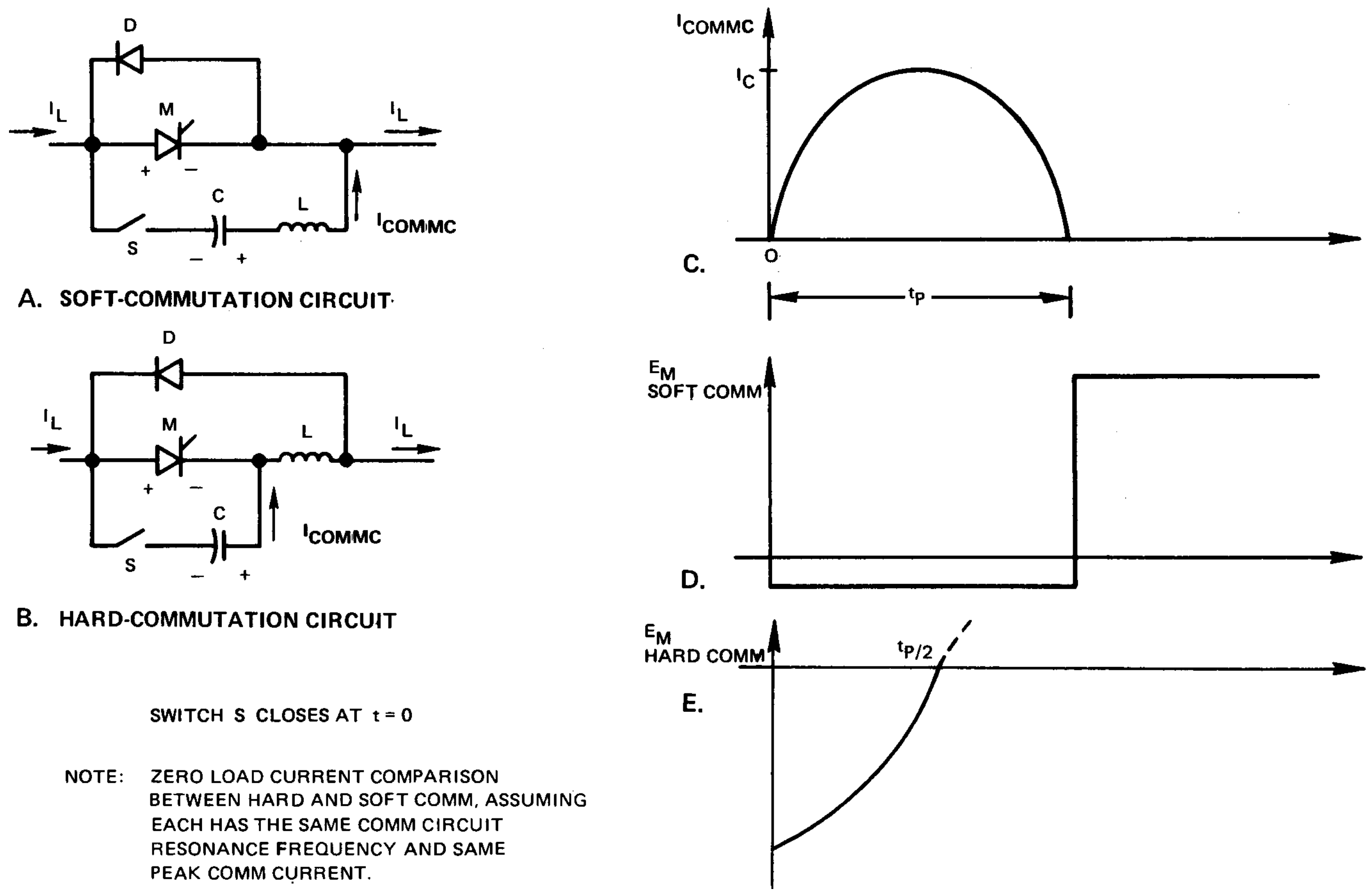


Figure 1. Example for Minimum Load

Figure 1E shows the thyristor commutation voltage available from the hard commutation circuit. It is apparent by inspection of Figures 1D and 1E that the hard commutation version provides a reverse voltage for only ½ $t_p$, or one-half the time available with the soft-commutation version, given equal values of commutation circuit inductance L and capacitance C.

COMMUTATION OF SIGNIFICANT LOAD CURRENT

When load current is considered, the action of both circuits is altered.

In the soft-commutated circuit, load current $I_L$ (Note 1) is gradually transferred from the main thyristor M to auxiliary device S while the commutating current $I_{COMMC}$ is increasing toward $I_C$. When the current through S is greater than the load current, the main device M is reverse biased by the forward voltage drop of diode D, and must be kept in that state for the required turnoff time $t_q$ of device M.

This may be expressed as follows:

$$\frac{t_r}{t_p} = \frac{180-2\sin^{-1}\frac{I_L}{I_C}}{180}$$

For a typical circuit, $I_C = 1.5\ I_L$; therefore, $t_q = .535\ t_p$

In the hard-commutated circuit, the load current $I_L$ (Note 1) is transferred immediately to device S and the commutation current increases toward its peak as in the soft commutated circuit. However, the load current immediately initiates a decay with time t of the capacitor voltage $e_c$ (and thus the commutating reverse bias voltage on thyristor M) at a rate expressed as follows:

---

(1) Load current ($I_L$) is assumed constant during the commutation interval.

$$\frac{E_{C_o}}{t} = \frac{I_L}{C}$$

where $E_{co}$ is the capacitor initial vooltage at time t = 0, before commutation.

Therefore, the commutation capacitor voltage can be expressed as follows:

$$e_c = E_{C_o} \cos \omega t - \frac{I_L t}{C}$$

The thyristor M is reverse biased so long as $e_c$ is greater than zero (Note 2), and the solution for t is the solution to the equation

$$0 = E_{C_o} \cos \omega t - \frac{I_L t}{C} \quad (2)$$

Solving for t yields

$$\frac{t}{\cos \omega t} = \frac{E_{C_o} C}{I_L}$$

for the time thyristor M remains reverse biased.

SOFT COMMUTATION EXAMPLE

For illustration, assume a hypothetical case with the following conditions:

$I_L$ = 2000 amperes
$E_{Co}$ = 3000 volts
C = 45μF

---

(2) In a practical case, the voltage must be 50 volts or greater to achieve optimum thyrsitor turnoff time.

Assume $\frac{I_c}{I_L} = 1.5$ ; so from the previous section, $t_q = .535\ t_p$.

$I_c$ also equals the capacitor voltage $E_{Co}$ divided by the circuit surge impedance, which is $\sqrt{L/C}$. Thus,

$$I_c = \frac{E_{C_o}}{\sqrt{L/C}}$$

Substituting in the above conditions and solving for L:

$$I_c = 1.5\, I_L = \frac{E_{C_o}}{\sqrt{L/C}}$$

$$1.5\,(2000) = \frac{3000}{\sqrt{L/45\mu F}}$$

$$(3000)^2 = \frac{(3000)^2}{L/45\mu F}$$

$$L = 45\mu H$$

Solving for the commutation current pulse width $t_p$ yields

$$t_p = \pi\sqrt{LC}$$

$$t_p = \pi\sqrt{(45 \times 10^{-6})\,(45 \times 10^{-6})} = 141.4\ \mu sec$$

Using the above expression for turnoff time,

$$t_q = .535\, t_p$$
$$t_q = .535\ (141.4\ \mu sec) = 75 \mu sec$$

HARD COMMUTATION EXAMPLE

Using the same conditions listed above for $t_p$, $I_L$, $E_{Co}$, C, and L, we can solve for the time t that the hard commutation circuit keeps thyristor M reverse biased for turnoff.

$$\frac{t}{\cos wt} = \frac{E_{C_o} C}{I_L}$$

Note:

$$\omega = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{(45 \times 10^{-6})\,(45 \times 10^{-6})}} = 22.2 \times 10^3$$

Thus, substituting in the known values and solving for t:

$$\frac{t}{\cos \omega t} \quad \frac{(3000)\,(45 \times 10^{-6})}{2000} = 67.5 \times 10^{-6}$$

$$t = 41\ \mu sec$$

The time t = 41µsec in the hard-commutation circuit is only 55% of the value $t_q$ = 75µsec obtained with the soft-commutation circuit. To achieve the same 75µsec reverse-bias time, the LC product of the hard-commutation circuit must be increased by the ratio $(75/41)^2$, or 3.3 times the LC product of the soft-commutation circuit.

However, thyristors used in hard-commutation circuits exhibit shorter turnoff times than when the same devices are used in soft-commutation circuits, because of the difference in reverse voltage. In addition, hard-commutation circuits permit a further reduction in thyristor turnoff time because of the lower reapplied dv/dt. These factors modify the hard- versus-soft comparison so that the difference in LC product may approach 1.5 rather than 3.3. Thus, approximately 50% greater commutation circuit energy storage capacity is required for the hard-commutation circuit in this type of application.

## CONCLUSION

Other factors in the comparison between hard and soft commutated circuits are given in the following chart. These conclusions are further supported by the comparison of the hard-commutated circuit studied (Circuit No. 9 in the chart on page 3-21) and the results of the EPRI 390-1 study. The hard-commutated circuits were eliminated as a class because of their higher cost and lower efficiency primarily due to the requirement for a 50% increase in commutation circuit energy storage capacity. The impact of substantial reverse recovery losses upon the power capability of a given large-area device in the hard commutation circuit is also a significant factor in the choice of soft over hard commutation.

CHART – COMPARISONS BETWEEN HARD AND SOFT COMMUTATION CIRCUITS

| HARD COMMUTATION |
|---|
| • **HIGH REVERSE VOLTAGE ON THYRISTOR**<br>• **HIGH LOSS IN THYRISTOR ASSOCIATED WITH TURN-OFF**<br>• **FASTER TURN-OFF THAN SOFT COMMUTATION**<br>• **LOW DV/DT FOLLOWING TURN-OFF**<br>• **COMMUTATION THYRISTOR SUBJECTED TO HIGH DI/DT'S** |
| SOFT COMMUTATION |
| • **LOW REVERSE VOLTAGE ON THYRISTOR (DIODE DROP)**<br>• **VERY LOW LOSS IN THYRISTOR DURING TURN-OFF**<br>• **SLOWER TURN-OFF THAN HARD COMMUTATION**<br>• **HIGH DV/DT FOLLOWING TURN-OFF**<br>• **COMMUTATION THYRISTOR HAS LOWER DI/DT'S** |

# APPENDIX C

## COMMENTS ON RP390-1 SELF-COMMUTATING CIRCUITS

## Comments on RP390-1 Self Commutating Circuits

The comments contained herein are based upon the assessment of the battery energy storage electrical requirements and the application of PSD's FCG-1 inverter technology to that application. The FCG-1 1 MW inverter power pole modified for operation over a dc voltage range of 2200 to 3500 was used as a basis of comparison. The FCG-1 commutation circuit is a variation of the Split-C type developed by PSD.

1. ACTRA Commutating Circuit

Power levels for the converters under consideration dictate the use of 65 mm to 75 mm thyristors. These larger devices have a higher recovered charge than the smaller devices used in the lower powered systems where circuits of this type have been previously applied. Since this is a hard commutation circuit, as stated in RP390-1, it must be designed to handle this recovered charge to prevent self-destruction of the device. This can be accomplished by using di/dt inductors to limit current rate during the recovery period. Soft commutated circuits such as the Westinghouse II, Split-C, and McMurray do not have this requirement.

There are twice as many shoot-through paths in the ACTRA as compared to the PSD Split-C circuit, and separate fusing of each path is required.

The commutating reactor must handle the full commutation current and voltage which makes it larger. It cannot achieve the same efficiency as the PSD Split-C.

2. Westinghouse II Commutating Circuit

This soft commutating circuit is similar to the Split-C circuit used in the FCG-1 inverter. However, variations of the basic circuit can result in different performance characteristics depending upon the application voltage and power levels.

In the RP390-1 version each main thyristor and diode device is subject to 1.5 Edc minimum voltage stress levels. The RP390-1 version requires four devices in series, whereas the PSD version requires only three due to the reduced stress levels. Also, the commutation devices need a series impedance to be properly snubbered. Additional components would be needed.

The input filter capacitor of this circuit compared to the PSD Split-C is subjected to the full commutation current, which is reflected in larger input filter losses.

3. Clamped McMurray Circuit

In general, the comments in RP390-1 are consistent with PSD's experience. It also should be noted that operation at other than unity power factor can cause large losses in the clamp resistor due to the load current modulation of the capacitor.

The commutation capacitor voltage can reach 2.5 times the input voltage. The combination of high voltage and current makes for a difficult capacitor design.

4. Clamped Siemens

Comments are similar to those on the Clamped McMurray.

5. Westinghouse 3

Comments similar to those for ACTRA except that the number of commutation thyristors needed is doubled.

## APPENDIX D

CIRCUIT DIAGRAMS OF OPTIONS SELECTED FOR
FURTHER CONSIDERATION FOLLOWING
THE PRELIMINARY EVALUATION

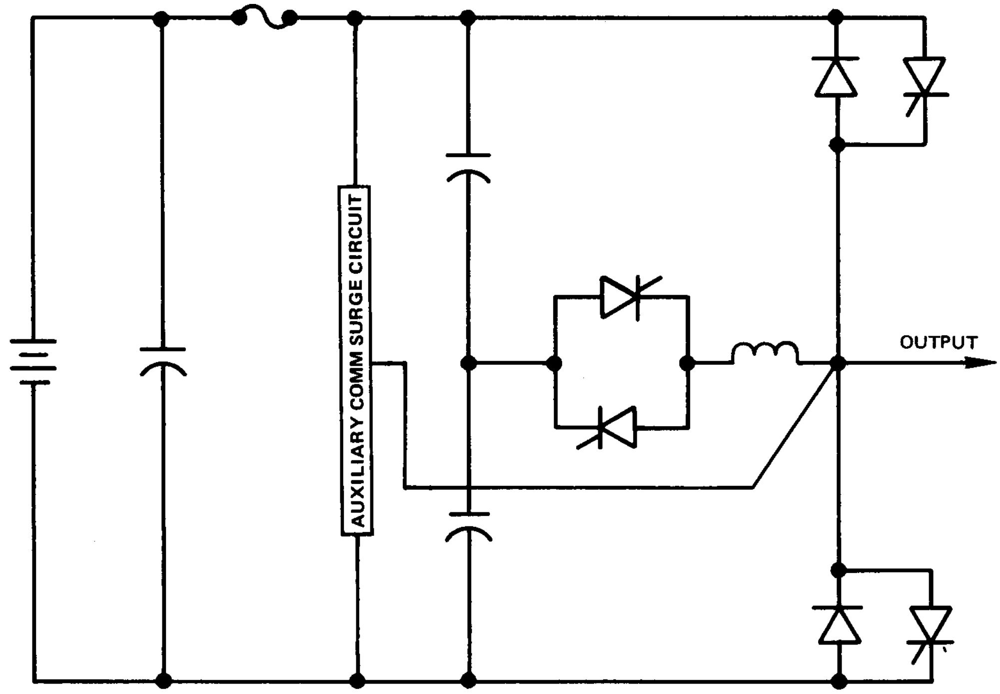


Figure 1. Auxiliary Commutation Circuit for Surge (Circuit No. 5)

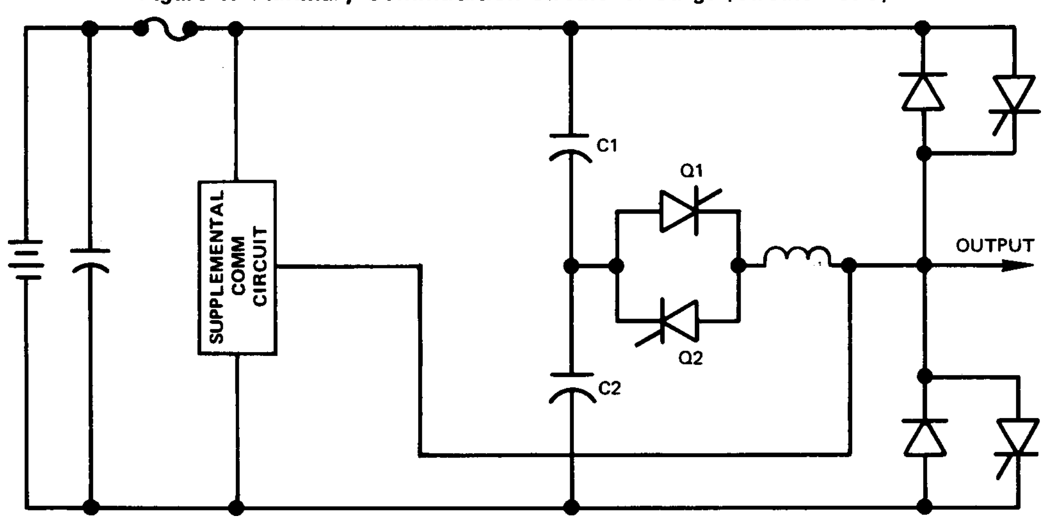


Figure 2. Controlled Commutation Energy (Circuit No. 3)

Note:

Circuit numbers correspond to those in Figure 3-6 of this report.

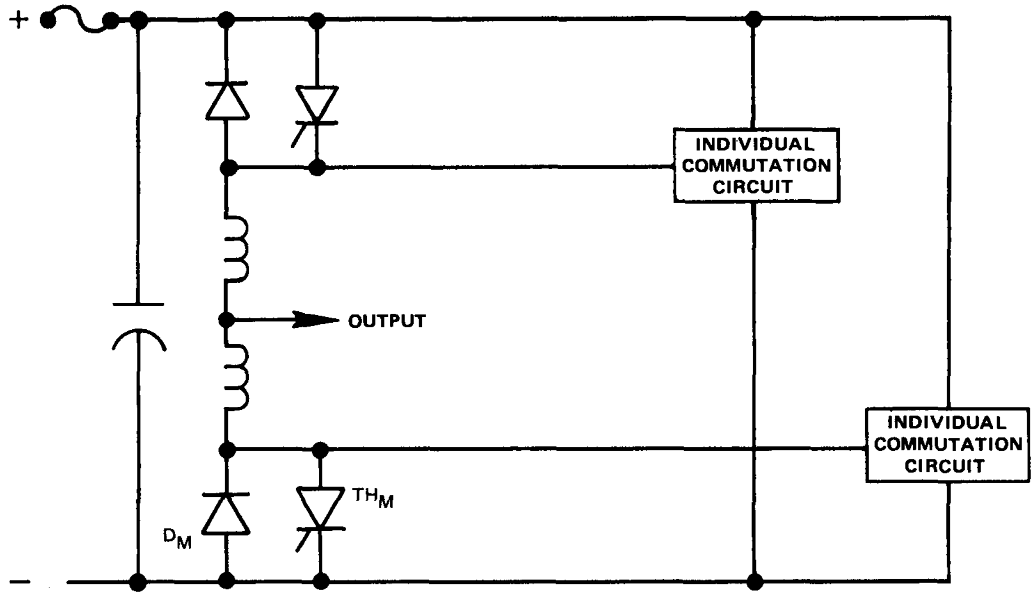


**Figure 3. Individual Commutation Circuit (Circuit No. 4)**

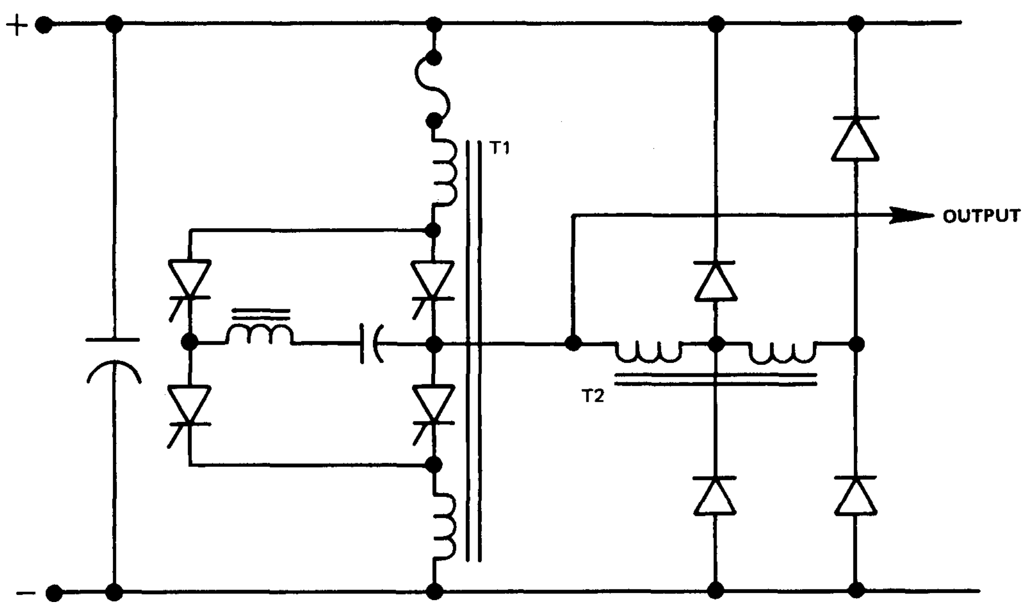


**Figure 4. McMurray Based Individual Commutation Circuit – Hard Commutation Version (Circuit No. 9)**

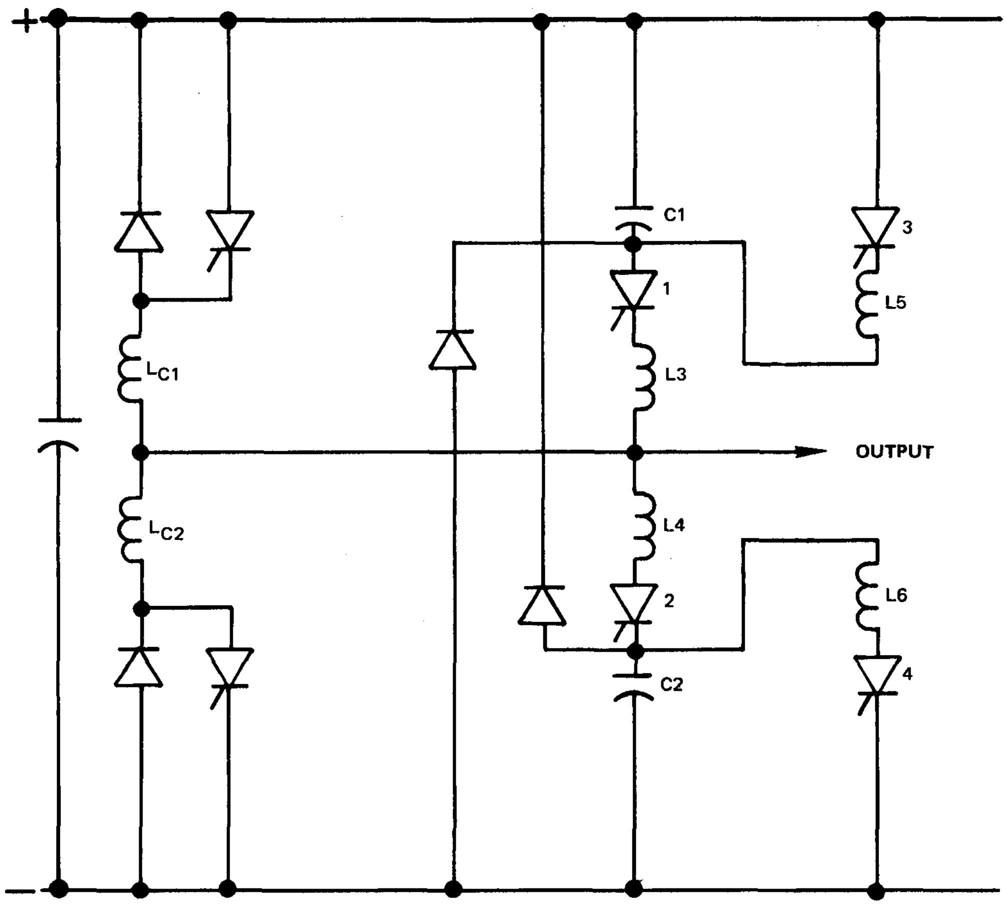


Figure 5. Extended Individual Thyristor Commutation Circuit (Circuit No. 7)

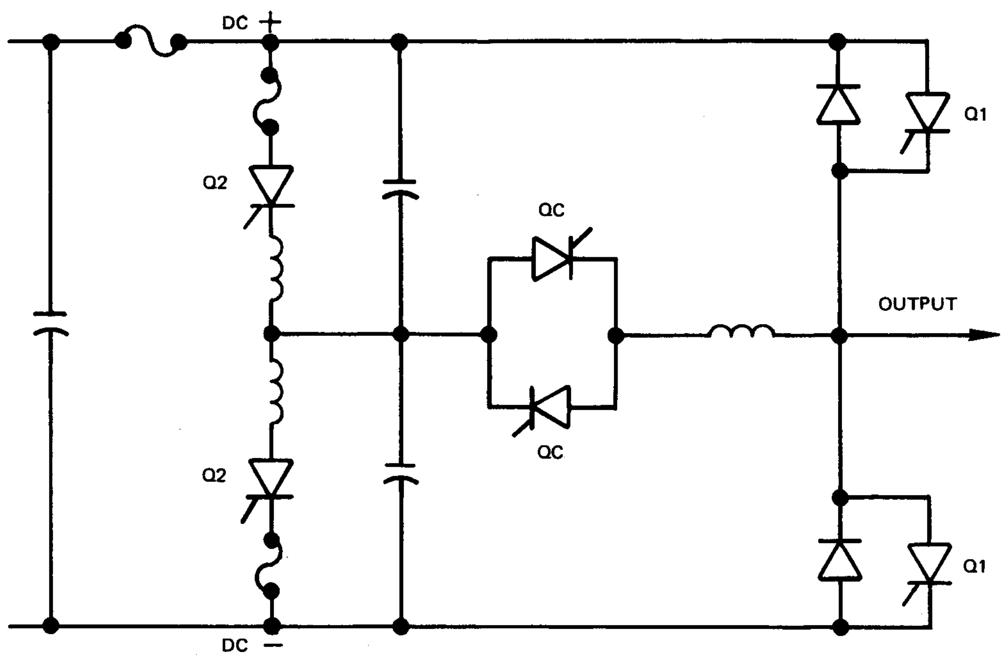


**Figure 8. Auxiliary Thyristor to Provide Makeup Pulse (Circuit No. 6)**

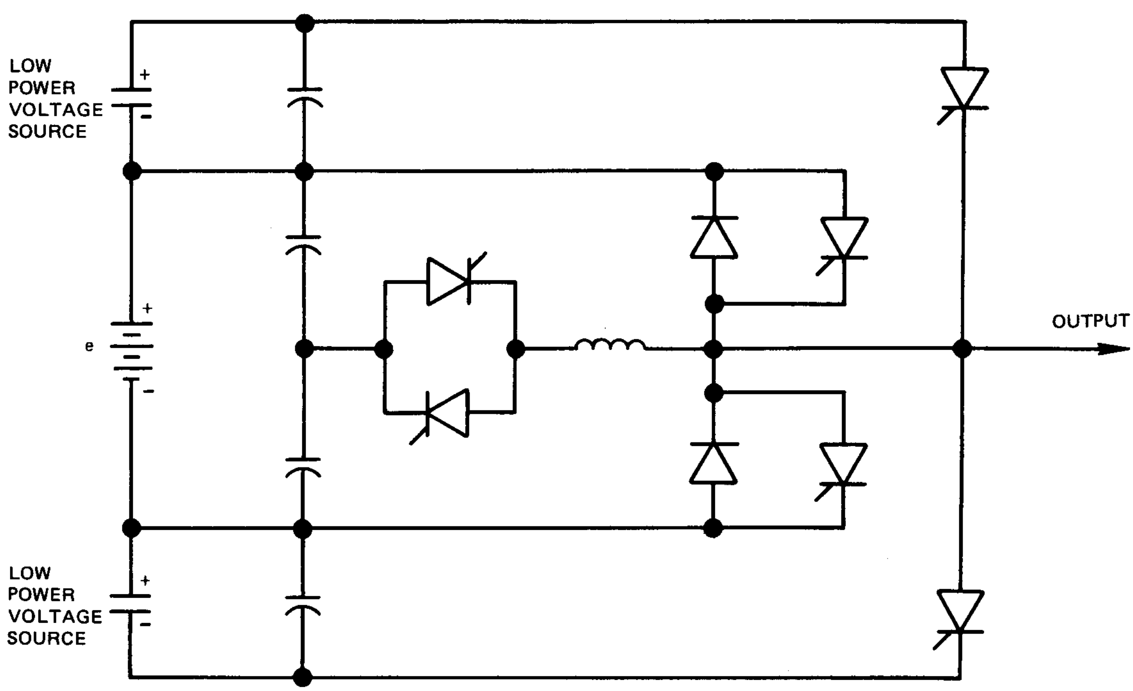


**Figure 9. By-Pass Commutation Circuit for Surges (Circuit No. 8)**

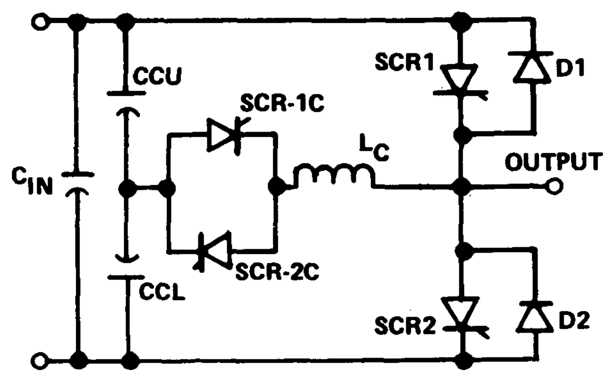


Figure 10. Baseline Split-C Pole

## APPENDIX E

REVISION TO ATTACHMENT A OF RP841-1
STATEMENT OF WORK

ATTACHMENT A

Revision 1
July 8, 1977

"Preliminary Specification for AC/DC Power Conversion Equipment for Batteries and Fuel Cells"

## INTRODUCTION

In application, it may be necessary or desirable that battery storage and fuel cell units be capable of operating isolated from the electric utility system. While we are not requiring this capability, the additional requirements of the conversion equipment for isolated operation are discussed in the specification. If design to these additional requirements would interfere with the ability to meet other basic objectives (e.g., cost), please provide a detailed discussion of the design changes required for isolated operation, the impact of the selling price of the complete unit with this feature, and results of studies with which you are familiar relative to the desirability of the isolated operation feature.

## GENERAL CONSIDERATIONS

The converter shall be designed to meet the following requirements:

Location and Operating Environment: Converter systems in the energy storage or fuel cell applications are expected to be located in remote unattended areas throughout the United States. The design should meet the following environmental criteria:

| | |
|---|---|
| Ambient Temperature, $^{o}F$ | -30 to $110^{o}F$ |
| Altitude | Up to 5000 feet (derate above 3300 feet) |
| Humidity | $80^{o}F$ Wet Bulb or 90% Relative Humidity |
| Wind, MPH (Side Wall) | 110 (45 $lbs/ft^2$) |
| Snow or Ice Roof Load, $lbs/ft^2$ | 80 |
| Wind, Simultaneously Applied with Snow and Ice | Calculate per Reference ANSI A58.1 for Room Configuration |
| Solar Radiation, $BTU/ft^2$-hr | 360 |
| *Seismic Loads (Ground Motion) | |
| Horizontal | 0.33G (2.1G) Max. without damping |
| Vertical | 0.22G (1.4G) |
| Dust micrograms/meter$^3$ | 180 |
| Salt Entrained in Air, ppm | .003 - .01 |
| Rain/Wind | 1 inch/hour/35 MPH |

*Seismic loads not simultaneous with wind loads.

Maintenance: Because of their expected location, the converter design must be easily maintained (i.e., its components and subsystems must be accessible), and required maintenance must be held to a minimum. Maintenance requirements should be appropriately balanced with equipment costs and reliability.

Acoustic Noise: The noise level generated shall be less than 55 db, "A-weighting" when measured at a distance of 100 feet from the installation perimeter.

Safety: Safety guidelines are to be established which minimize the occurrence of a hazardous event. A hazardous event is defined as either a serious personal injury or major equipment damage. No single failure should result in a hazardous event.

Design guidelines are to be consistent with NEMA, ANSI, OSHA, National Electrical Safety Code, and ASME when applicable.

## COST AND LIFE CONSIDERATIONS

Cost: The cost of all equipment necessary for the conversion process, as defined in the Statement of Work, Section 1.1, should not exceed $60/kW.* The cost should be the selling price to the user for mass produced equipment in a mature technology (i.e., not a "first-of-a-kind" product).

Power Rating Base: For batteries, the power base used to determine the specific cost of the equipment should be the converter rating at the beginning of the discharge cycle. For fuel cells, the power base used to determine the specific cost of the equipment should be the converter rating at the cutoff voltage required to result in an acceptable heat rate for the design.

Life: The expected life of the equipment should not be less than 20 years with nominal maintenance, repair.

Modularity: Modularity is encouraged to enhance maintainability and reliability. The occurrence of full- and partial-station outages caused by converter failures should be limited by a modular approach.

## ELECTRICAL CONSIDERATIONS

DC Voltages: The minimum dc bus voltage shall be a nominal 2200. The maximum value shall be established by the dc voltage range described below. The minimum dc voltage may be adjusted to provide design flexibility for accommodating the widest range of battery operating conditions.

*This cost is given in 1975 dollars.

DC Voltage Range: The ratio of maximum to minimum voltage during battery operation is:

a. 1.7:1 For 7 hrs charge 5 hr discharge profile from top-of-charge to end-of-discharge.

b. 1.6:1 For 7 hr charge 10 hr discharge profile from top-of-charge to end-of-discharge.

The maximum to minimum voltage ratio during battery discharge is:

a. 1.3:1 For 7 hr charge, and either 5 hr discharge profile or 10 hr discharge from top-of-discharge to end-of-discharge

The maximum to minimum voltage ratio for the fuel cell is:

a. 1.3:1 For fuel cells from minimum-load to full-rated load, over the life of the equipment.

Power Rating: The nominal converter system rating is 27 MW ac at unity power factor. Reactive power generation capability is to be determined. For batteries, the converter will be rated at the beginning of discharge. For fuel cells, the converter will be rated at the 100% power point.

AC Voltage: The design should be for operation into a 3$\phi$, 13.8 kV (nominal), 60 Hz utility system. As alternates, consider changes in design required for operation into 34.5 kV and 69 kV systems and explain the impact on design and costs for operation at these higher voltages.

AC Voltage Range: Operation is expected to be at distribution voltage levels. Voltage regulation on distribution systems is not as continuous as on transmission networks. To accommodate anticipated voltage regulation needs on distribution systems, these line voltage/performance criteria will be followed:

Line Voltage Range

±5% normal continuous, no effect on performance
+5% to +10% (maximum continuous, up to 85% of rated power output at unity power factor).
-5 to -10% (Maximum acceptable continuous, up to 95% of rated power at unity power factor).
-10 to -20% (short time operation up to 85% of rated power output at unity power factor).
$>$+10%, $<$ -20% (not acceptable, power conditioner may turn off).

AC Voltage Unbalance: One per unit ac power will be maintained with a 2 percent phase-to-phase voltage unbalance.

Power Factor Correction (PFC): PFC should be supplied so as to control the power factor at the ac side of the transformer to a level no worse than .9 lagging. Leading power factor operating capability may be desirable. Near-unity power factor operation most of the time is preferred, unless such a feature interferes with attainment of other goals (e.g., cost).

Efficiency: 95% conversion efficiency (one way) is required at full-load operation. At 25% load, the efficiency should not fall below 90%.

Harmonics: Harmonic voltages introduced into the utility ac network should not exceed, in total, 4 percent RMS of the fundamental on power systems at 13.8 kV levels. Filters, if needed, should be provided and clearly identified for this purpose.

Electromagnetic Interference (EMI): The converter design shall not result in misoperation of local utility and consumer communications equipment.

## OTHER CONSIDERATIONS

Cooling: Appropriate choice of cooling techniques should be employed to allow suitable performance of the equipment. In any event, the final heat transfer will be to ambient air.

Protection and Protection Coordination:

Protection - The converter system shall have three primary zones of protection.

1. DC source and buswork
2. Power conditioner
3. AC system and its protection

The converter system is to be designed such that its protection system is coordinated in an overall systems plan to correct automatically for internally or externally generated malfunctions which could cause operation of any zone beyond its design capability.

DC input - The inverter system should provide protective device(s) to interrupt the fault current of the dc source for inverter internal faults. The dc source is to contain a means for preventing one dc submodule or the ac source from contributing to a fault in a dc submodule. A transient impedance between that range representative of a fuel cell and a lead acid battery will be used as a baseline.

SCR protection - Power SCR's shall be protected against burnout due to faults or overload conditions. Fuses are to be coordinated so as not to clear during ac system operation under all normal and abnormal conditions including distribution line faults and recovery and most lightning strokes. These fuses shall be easily accessible for inspection, maintenance and replacement. Protection trip indication shall be provided.

AC Protection - The converter system output shall contain circuit breaker and differential protection against short circuits and faults in the ac side of the inverter system. The circuit breaker shall be capable of interrupting the fault current of the ac system short circuit capability.

Isolated Operation: Comments related to isolated operation are deferred pending their consideration in a companion ERDA program.

## SAMPLE V/I CHARACTERISTICS

Sample V/I characteristics for a battery cell are shown in Figure 1. Information for a fuel cell module is shown in Figure 2. This data serves to identify the points which have been discussed in this document: the rating bases, maximum and minimum voltages, full load points, etc.

Duty Cycle: As indicated in Figure 1 the baseline cycle for the application is the 7 hr charge followed by a 3 to 5 hr taper and a 10 hr discharge. The requirements for an identical charge cycle followed by a 5 hour discharge are also to be considered.

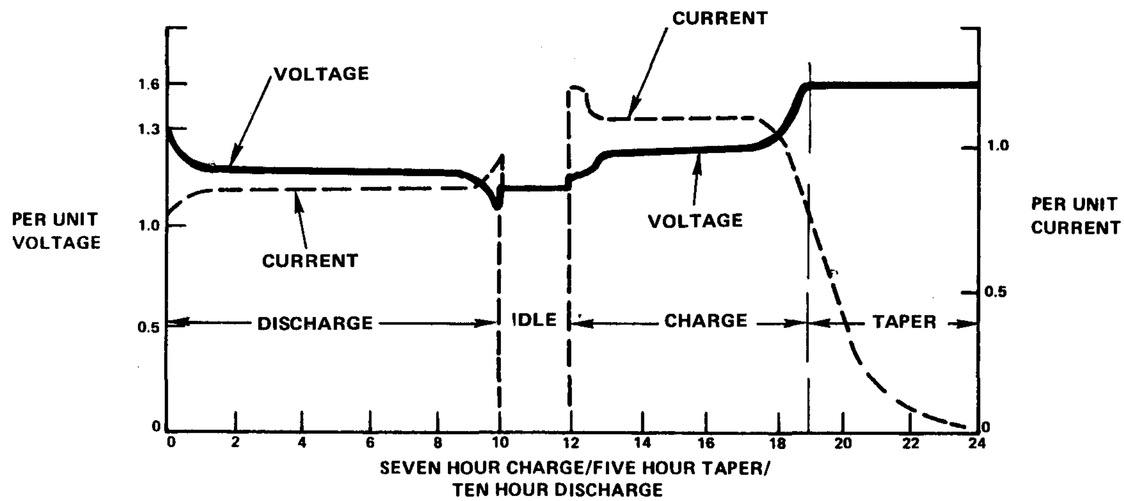


Figure 1. Sample V/I Characteristics for a Battery Cell

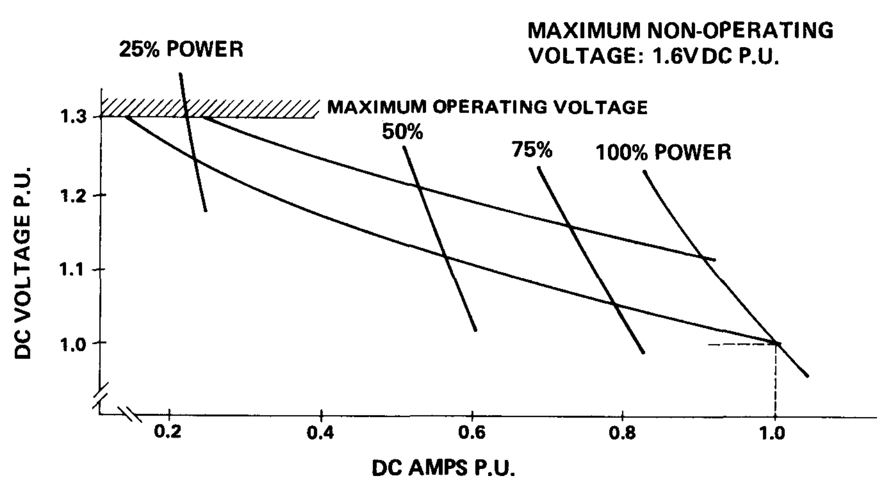


Figure 2. Sample V/I Characteristics for a Fuel Cell