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REDUCTION OF SHIPBOARD 400-HZ POWER REQUIREMENTS EXECUTIVE OVER--ETC(U)

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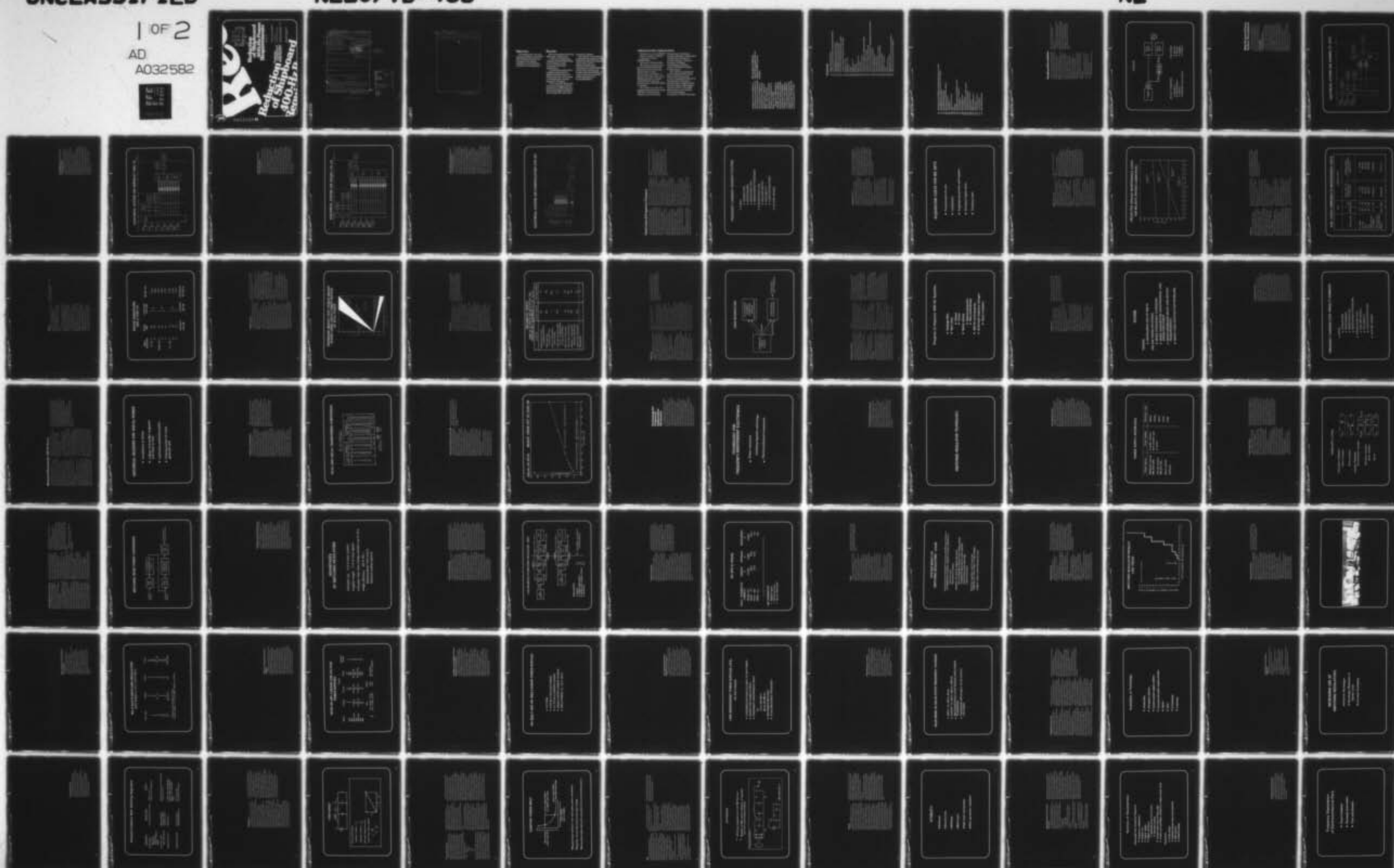

# Reduction of Shipboard 400-Hz Power Requirements

NELC/TD 488

EXECUTIVE OVERVIEW

1 October 1976

Prepared for NAVSEA 0331

Naval Electronics Laboratory Center
San Diego, California 92152

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Excessive costs and system penalties are associated with 60-Hz to 400-Hz shipboard frequency changers. Data on these costs and penalties is provided. Methods are explored to reduce the need for both motor-generator sets and solid-state frequency changers.

The use of a new technology, switching mode power supplies, shows considerable promise as a method of eliminating the need for frequency


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changers. These switching regulator power supplies, which are being used in shipboard electronics for other purposes, are discussed.

The need for shipboard frequency changers can be cost effectively reduced on Navy surface ships throughout the fleet in a time period approximating the life cycle of an electronic system.

## Objective

Investigate the cost and system penalties associated with shipboard frequency changers and explore methods of reducing the need for such equipment.

## Results

The investigation drew the following conclusions:

a. The use of frequency changers aboard Navy ships is excessively costly compared with other approaches.

b. Switching mode power supplies being used in shipboard electronics for other purposes can be used to eliminate the need for frequency changers.

c. The need for shipboard frequency changers can be reduced cost effectively in a time period approximating the average life cycle of an electronic system.

This report recommends taking the management and technical steps necessary to reduce the need for shipboard frequency changers. It is hoped that thi report will convince the reader of the desirability of such a reduction and will enlist his support in accomplishing it.

## *Administrative Information*

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The work was under the technical management of the NAVSEC Ship Systems Engineering and Design Department, Machinery Systems Division, Submarine and Electrical Systems Analysis Branch, Systems Analysis and Deep Submergence Vehicle Section, NAVSEC 6156D, F Henrickson.

The work was performed by the authors at the Naval Electronics Laboratory Center, Engineering Sciences Department, Advanced Mechanization Applications Division, Power Electronics Branch, NELC Code 4340. Maintenance cost studies were performed by GL Ruptier of NELC Systems

Analysis Group. Studies on *the frequency dependency of* electromagnetic components were made by J Simpson, a San Diego State University student under contract to NELC. Ship electrical systems were described by ET Staub on assignment to NELC Code 4340.

Numerous individuals at NAVSEC provided valuable data for the report. JA Brady and M Spivak of NAVSEC 6156D were very helpful in coordinating this NAVSEC support. Personnel from the David Taylor Naval Research and Development Center, Electric Systems Branch, Code 2781, provided data on shipboard 400-Hz power systems.

# Contents

# Problem Description

Except on a few small high-performance ships such as hydrofoils and surface-effect ships, the shipboard prime electrical power for Navy ships is supplied by turbine generators with three-phase, 60-Hz, 450 Vac output. Most shipboard machinery and electronic systems use 60-Hz power, but there are some that require 400-Hz power. For these loads a 60- to 400-Hz frequency changer, usually a motor-generator (MG) set, is used. MG sets typically have poor reliability and maintainability, logistic problems, and undesirable load coupling that is attributable to source impedance effects.

To alleviate these major problems, the Navy is conducting a variety of programs that include

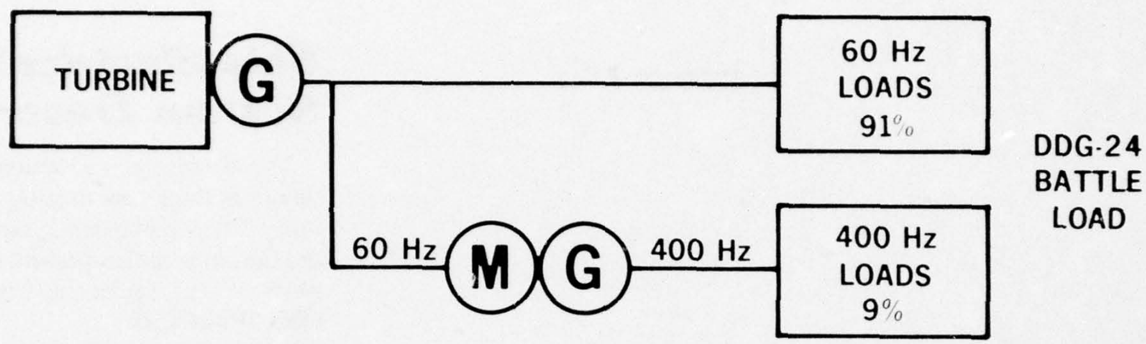
a. Redesigning the MG sets as well as improving them with modification kits.

b. Replacing the MG sets with solid-state frequency changers.

c. Combining frequency changers with other components such as passive and active filters, to give better system performance.

This program investigates the possibility of eliminating the need for frequency changers by using other technologies, and shows that those technologies are available. The high cost of frequency changers is emphasized to stimulate effective action toward reducing their use in future Navy ships.

## PROBLEM




### MG SET PROBLEMS

- RELIABILITY
- MAINTAINABILITY
- LOGISTICS
- UNDESIRED LOAD COUPLING

### SOLUTIONS

- IMPROVE
- REPLACE
- COMBINE
- ELIMINATE

## Ship Electrical Power System Descriptions

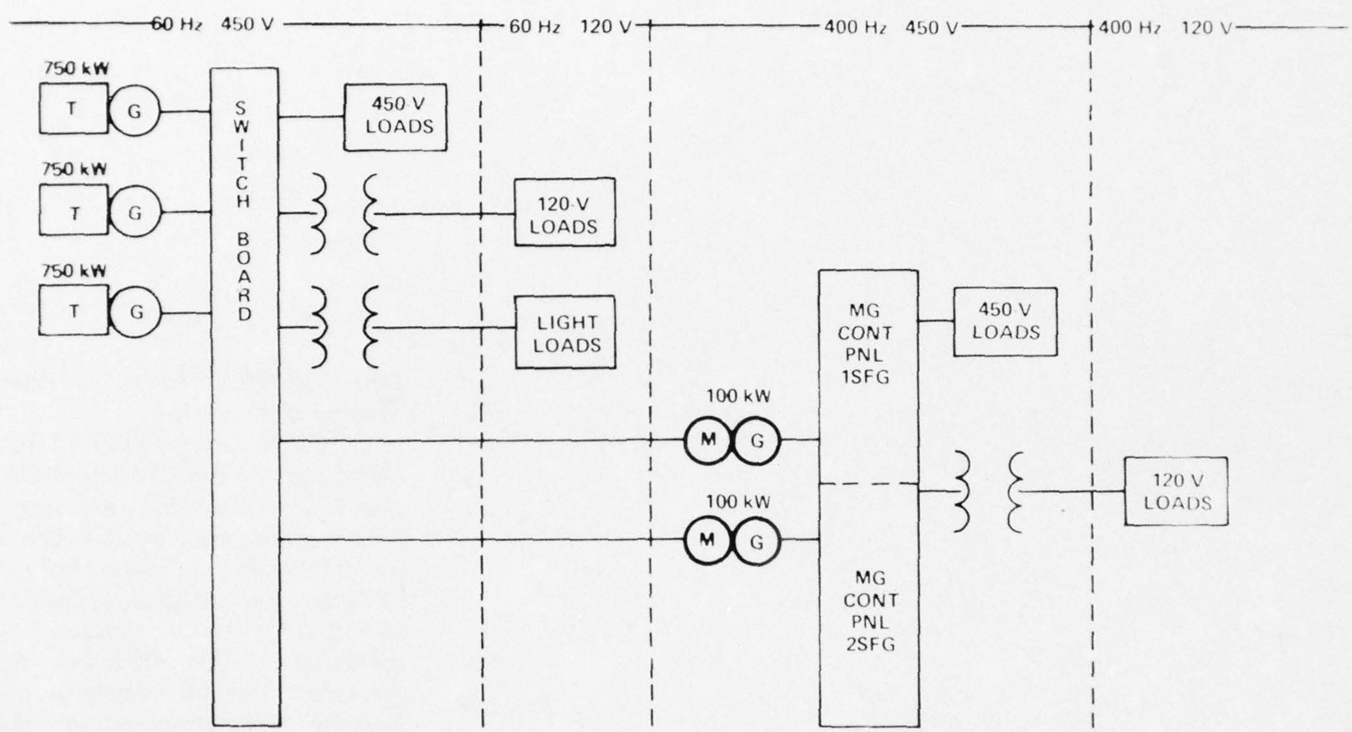
The electrical power systems of four classes of ships were investigated in the study. The accompanying simplified one-line drawings each represent the power system of a particular ship from each class.

***USS DOWNES***

***Electrical Power System***

USS DOWNES is an FF 1052 Knox class frigate—a class designated as ocean escorts (DE) prior to July 1975. The 46 frigates in this class constitute the largest group of frigates built to the same design since World War II. The ship's primary power is 60 Hz ac—provided by three ship service 750-kW turbine generators. The 400-Hz system is powered from the 60-Hz system and consists of two 100-kW motor-generators (MGs) and associated switchboards, control panels, and distribution cables. The connected load of the 400-Hz system is about 8 percent of the ship's total connected load.

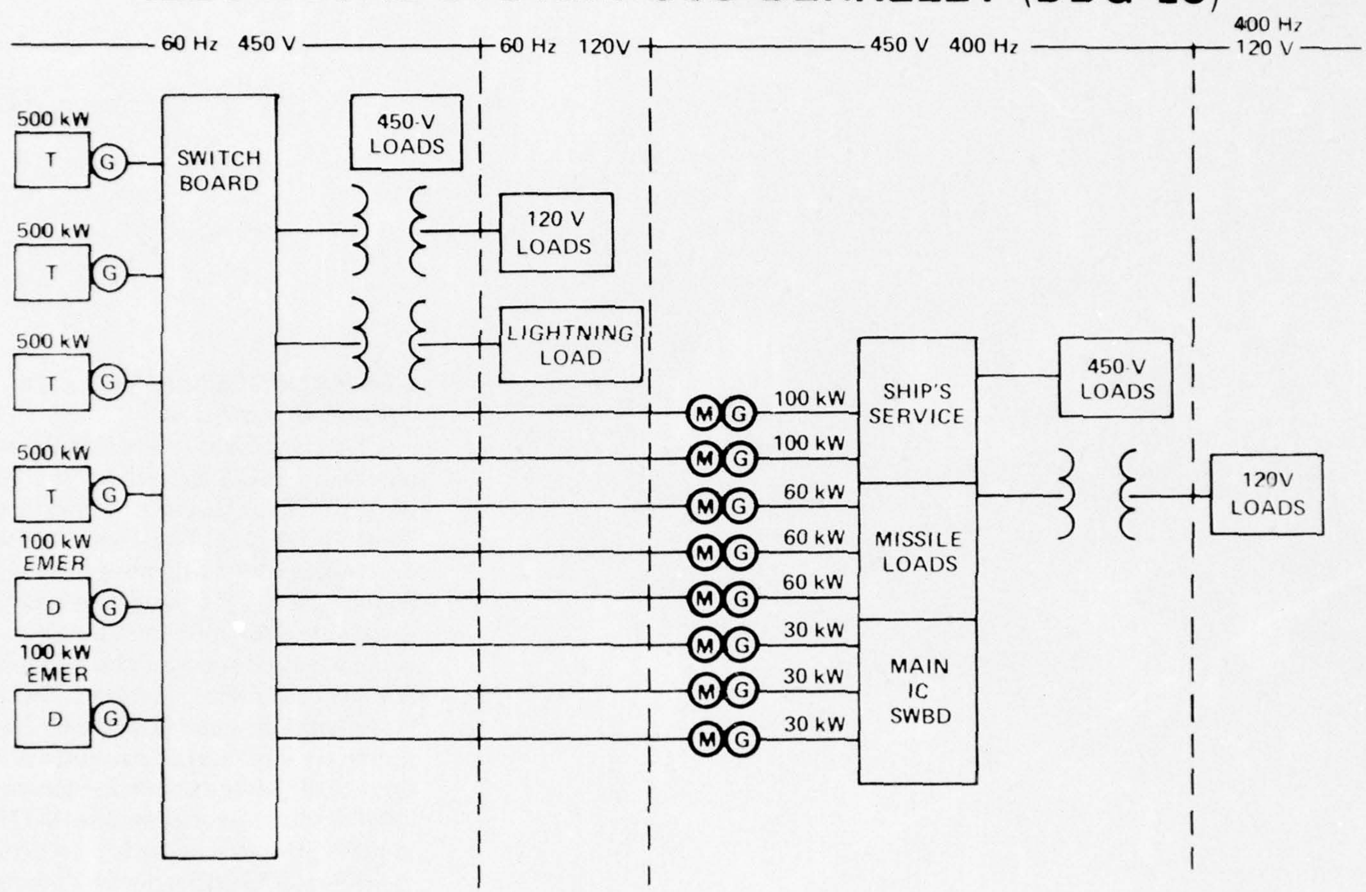
## ELECTRICAL SYSTEM USS DOWNES (FF 1070)



### ***USS BERKELEY Electrical Power System Description***

USS BERKELEY is a DDG 2 Adams class destroyer. The 23 destroyers in this class are considered to be excellent multipurpose ships. The ship's primary power is 60 Hz ac—provided by four 500-kW turbine generators, two power switchgear groups for control and distribution, and two 100-kW emergency generators. The 400-Hz system is powered from the 60-Hz system and consists of two 100-kW MG sets for ship service power and three each 60-kW and 30-kW MG sets for special-purpose 400-Hz requirements. The connected load of the 400-Hz system is about 4 percent of the ship's total connected load.

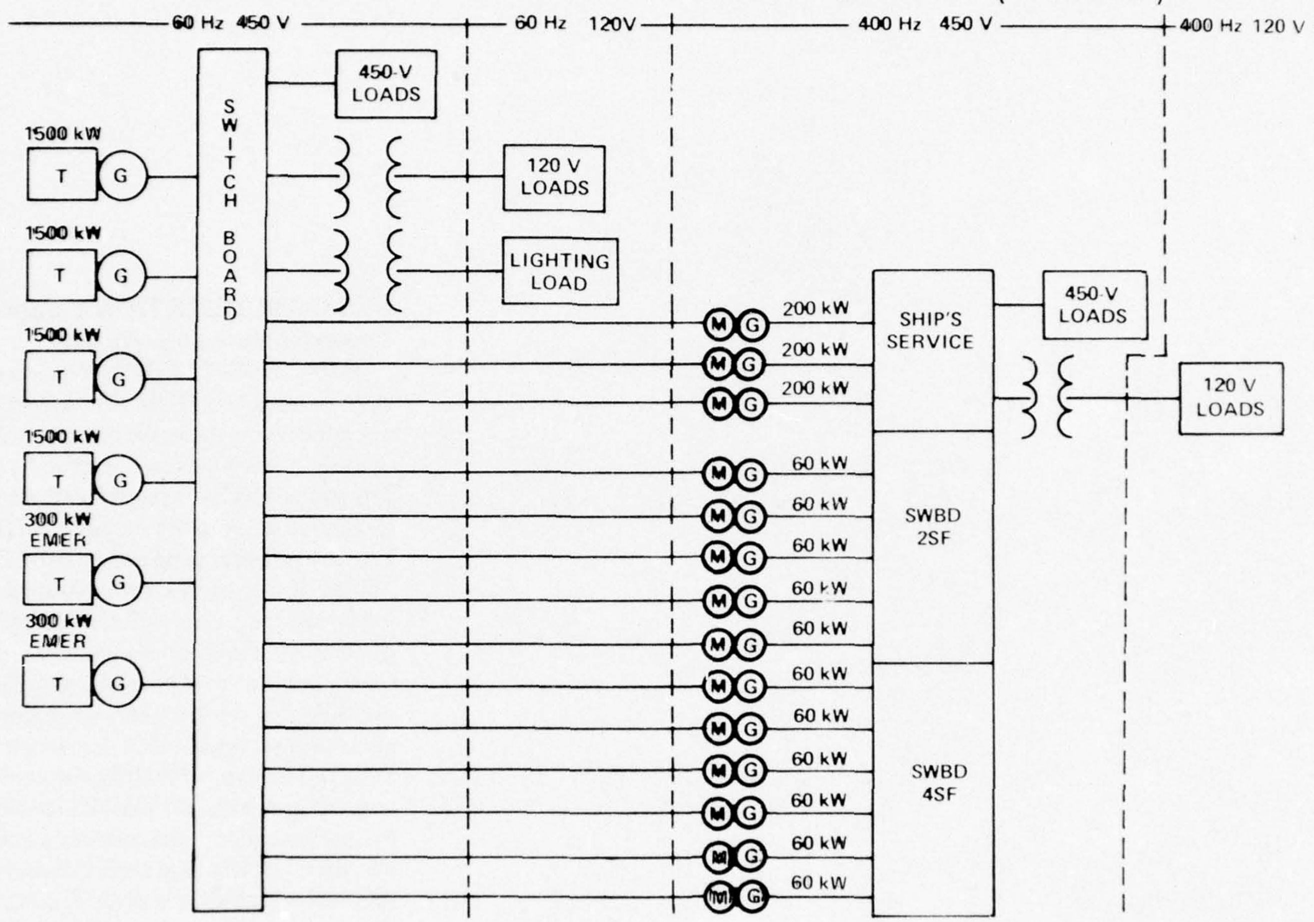
## ELECTRICAL SYSTEM USS BERKELEY (DDG 15)



### *USS HALSEY Electrical Power System Description*

USS HALSEY is one of nine ships reclassified as CG 16 Leahy class cruisers on 1 July 1975. They are referred to as "double-ended missile cruisers" and were originally classified as guided missile frigates (DLGs). Primary power is 60-Hz—supplied by four 1500-kW turbine generators with two emergency backup 300-kW gas turbine generators. The 400-Hz system is powered from the 60-Hz system and consists of three 200-kW MG sets for ship service power and eleven 60-kW MG sets for special-purpose 400-Hz requirements such as the MG set dedicated to the AN/SPG-55B radar cw illuminator. The connected load of the 400-Hz system is about 13 percent of the ship's total connected load.

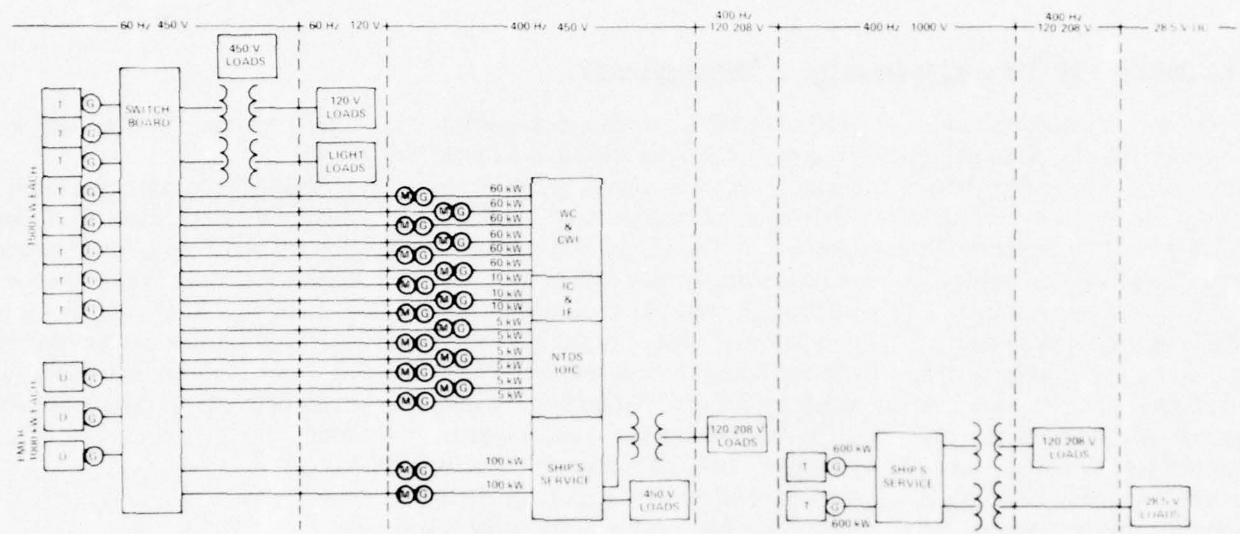
# ELECTRICAL SYSTEM USS HALSEY (CG 23)



### *USS CONSTELLATION Electrical Power System Description*

USS CONSTELLATION is one of four ships in the CV 63 Kitty Hawk class of aircraft carriers currently being modified to operate as multipurpose aircraft carriers. These ships all have highly sophisticated electronic equipment, including NTDS. Primary power is supplied by eight 60-Hz 1500-kW ship service turbogenerators and, for emergency, three 100-kW diesel generators. The ship has a 400-Hz prime power system consisting of two 400-Hz 600-kW ship service turbogenerators. It also has a secondary 400-Hz system powered from the 60-Hz system and consisting of two 100-kW MG sets for ship service power and, for special needs, six 60-kW, three 10-kW, and six 5-kW dedicated MG sets—15 MG sets in all. The combined installed capacity of these 400-Hz MGs is about 14 percent of the ship's total installed capacity excluding aircraft needs.

# ELECTRICAL SYSTEM USS CONSTELLATION (CVA 64)



## Total Costs of Frequency Changers

The four ship studies just delineated were used as a data base for determining the total costs associated with the 1546 MG-set frequency changers supplying 400-Hz power on 383 Navy surface ships. Total costs consist of monetary ones, referred to below simply as "costs," and nonmonetary ones, referred to as system penalties.

Costs are incurred for acquisiton and replacement of these MG sets, as well as for their maintenance and operation. Installation or replacement of MG sets often requires opening of the ship's hull. Navy personnel training to maintain and operate MG sets has been unusually expensive because there are 195 different MG-set designs in the fleet. Costs relating to acquisition, maintenance, and operation (particularly fuel costs) are discussed later in more detail.

System penalties are factors that impact the design and effectiveness of the ship as a weapon system—factors such as weight, volume, reliability, and load interaction. Frequency changers such as a 300-kW MG set can weigh as much as 17 500 pounds (7.9 Mg) and occupy as much as 210 cubic feet (6 $m^3$). The weight and volume are not much less for the newer solid-state frequency changers when individually compared with MG sets that have the same kilowatt rating. The poor reliability of MG sets is a significant system penalty. In a 1976 Navy Maintenance and Material Management (3M) report, which ranks all shipboard equipment so as to point up the top 300 problem equipments of the Navy, 60- to 400-Hz MG sets ranked 73. Interaction between loads is more prevalent on 400-Hz systems than on 60-Hz systems; Mg sets frequently have been utilized as filters—dedicated exclusively to single electronic loads. This filtering function and redundant requirements have produced a proliferation of MG sets aboard ships. Weight, reliability, and load interaction are discussed later in more detail.

The 400-Hz connected loads in the first three ships studied were 8, 4, and 13 percent of the ships' respective total connected loads. Future costs and penalties will be affected by the trend to specify 400-Hz power for electronic equipment, a trend which will increase these percentages. This is commented on later.

## FREQUENCY CHANGER TRADEOFF FACTORS

- COSTS
  - ACQUISITION
  - MAINTENANCE
  - OPERATING FUEL
  - IMPROVEMENT PROGRAMS
- SYSTEM PENALTIES
  - SIZE AND WEIGHT
  - RELIABILITY
  - LOAD INTERACTIONS
- FUTURE TRENDS

### *Acquisition Costs*

Costs are incurred when frequency changers are installed either initially or on replacement. The costs are high because of the many MG sets used per ship. As many as 17 are required on a CG class ship, which carries a Terrier missile system. Other ships have as many as 33 MG sets. Installation of newer solid-state frequency changers should decrease the number of MG sets required by an as yet undetermined amount.

Unit procurement is only part of the one-time acquisition costs. Installation or replacement of MG sets often requires opening of the ship's hull. For this reason, the Navy's standard solid-state frequency changers are being designed to go through 30- by 30-inch hatches and 26- by 45-inch doors.

Other acquisition costs are associated with engineering support, repair parts, and crew training. These costs, particularly those for crew training, are magnified by the 195 designs—and the 195 associated technical manuals—from 30 different manufacturers of the present 60- to 400-Hz MG sets in the fleet. Most of the newer MGs are being manufactured by only three companies. The Navy's standard solid-state frequency changers have been optimized for minimum life-cycle costs. For example, they have a single design configuration for all sizes. This standardization will greatly reduce training costs.

## ACQUISITION COSTS FOR MG SETS

- Procurement of unit
- Installation
- Engineering services and support
- On-board repair parts
- Training crews

### *Maintenance Costs*

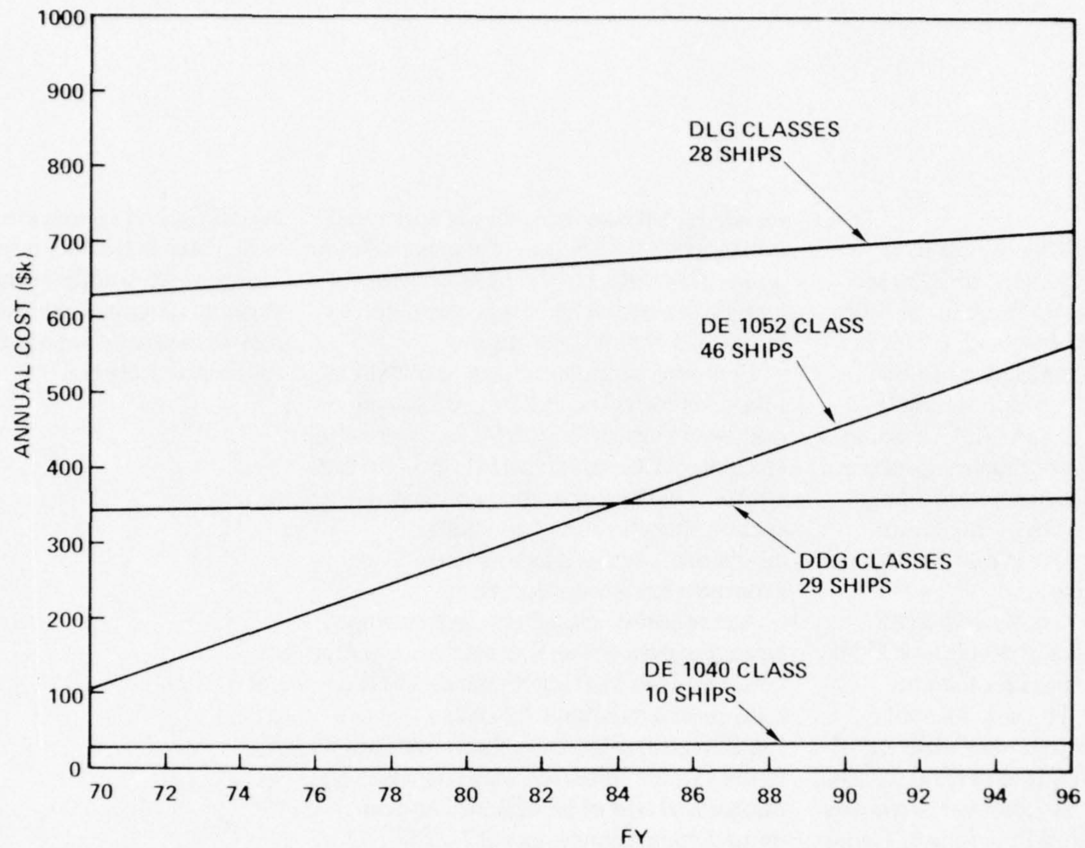
Maintenance costs are a large part of the overall 400-Hz system costs. Excessive maintenance costs have occurred because of the high MG failure rate and the complex logistics of supporting the many different MG set designs. To get and keep the MG sets going has required highly specialized teams from NAVSEA, NAVSEC, shipyard and support facilities, and the fleet.

A statistical analysis was performed to project future annual maintenance costs for four selected ship types. It used pre-July 1975 class designations so as to tie in with the cost data references.

The DE 1040 class was included to provide more representative statistical data. (Since it does not have high-power radars or missiles like the other classes, its inclusion results in a better cross section of ships that use MG sets.) The CV class was excluded because it has only a few ships and low uniformity of armament and radars.

The components of annual maintenance cost—scheduled and corrective maintenance parts and labor, as well as overhaul costs—were totaled for each of the 3 years, FY 73 through FY 75. A NAVSEC study provided the labor rate: $20 per hour for FY 75, deflated 10 percent per year for FY 74 and FY 73. It includes ship, tender, and some shipyard support costs. The three totals were time plotted, and a least-squares line was fitted to each set of points. (Similar graphs based on one higher labor rate and one lower one were plotted to show the sensitivity of the total cost to a change in hourly labor rate.)

## PROJECTED ANNUAL MAINTENANCE COSTS FOR MG SETS [NAVSEC LABOR RATE]



***Fuel Costs***

Fuel costs are among the main operating cost components of 400-Hz electric power systems. The low efficiency of shipboard MG set frequency changers—66 to 88 percent at full load, 61 to 85 percent at half load—proportionately increases the fuel consumed. Comparable additional fuel consumption may occur for the Navy's solid-state frequency changer, which is specified to have a minimum efficiency of 80 percent at rated loads and 70 percent at half loads.

Annual fuel costs attributable to the inherent power losses of 60-Hz to 400-Hz MG sets were computed for the four selected ship types. The ship's steam turbines require 0.9 pounds (0.405 kg) of marine diesel fuel (DFM) per kilowatt-hour. A basic fuel cost of $14.238 per barrel was quoted by the Defense Fuel Supply Center. This price includes transportation costs to the first delivery point as well as some other expenses, but does not include additional transportation costs from the initial delivery point to the ship. On the basis of these figures, the cost of DFM was calculated to be $0.043 per kilowatt-hour.

Pertinent parameters such as individual MG set efficiencies and annual kilowatt-hours consumed by each MG set were also calculated. Consideration was given to the effects of various operating conditions—anchor, shore, cruising, and battle conditions—on load factors and proportionate annual hours.

A comparison based on the four ship types analyzed shows that total annual fuel costs ($1 064 343) are 89 percent of the total annual maintenance costs ($1 200 689). Projecting these costs to all of the surface ships with MG sets yields an annual fuel cost of $2 426 702 and an annual maintenance cost of $2 737 571.

These computed operating costs are augmented by the indirect cost of the ships' added cooling system loads imposed by heat losses in the MG frequency changers. This necessary added cooling system capacity requires its share of equipment, maintenance, and electrical power (with its associated fuel cost).

# FUEL COSTS COMPARED TO MAINTENANCE COSTS

| | QTY | | ANNUAL COST | |
|---|---|---|---|---|
| SHIP CLASS | SHIPS | MG SETS | FUEL DUE TO INEFFICIENCY OF MG SETS | MAINTENANCE FY-75 USING NAVSEC LABOR RATE |
| DE 1040 | 10 | 20 | $ 7 085 | $ 29 944 |
| DE 1052 | 46 | 92 | 161 024 | 195 053 |
| DDG | 29 | 214 | 221 697 | 343 053 |
| DLG | 28 | 351 | 674 537 | 632 639 |
| TOTALS FOR 4 CLASSES | 113 | 677 | $1 064 343 | $1 200 689 |
| TOTALS FOR ALL SURFACE SHIPS | 383 | 1546 | $2 426 702 | $2 737 571 |

### *Weight*

A primary purpose of going to 400 Hz in the past was to save weight in the electronics equipment. But because frequency changers were then required, the overall result was to increase total ship weight.

To illustrate, the weights of the MG sets are shown for a typical guided missile destroyer such as USS BERKELEY, DDG 15. The added weight on each of the 23 ships of this class is 30 700 lb (13.8 Mg).

Frequency changers also occupy considerable shipboard volume. For the ships described above, each requires 375 cubic feet (3 $m^3$ ) of space to house the MG sets plus additional room for access. Furthermore, the weight and cost of cables, panels, connectors, and other hardware associated with the 400-Hz power distribution system must be considered.

In the following trade-off discussion, the weight penalty of frequency changers is compared with the weight savings in electronics equipment.

## MOTOR GENERATORS
## DDG-2 THRU 24

| Motor Generator | Rating (kW) | Connected Load (kW) | Weight (lbs) |
|---|---|---|---|
| S/S MG #1 | 100 | 43 | 5,000 |
| #2 | 100 | | 5,000 |
| MISSILE MG #1 | 60 | 80 | 3,600 |
| #2 | 60 | | 3,600 |
| #3 | 60 | | 3,600 |
| IC/FC MG #1 | 30 | 37 | 3,300 |
| #2 | 30 | | 3,300 |
| #3 | 30 | | 3,300 |
| | 470 kW | 160 kW | 30,700 lbs |

## *Weight Trade-off*

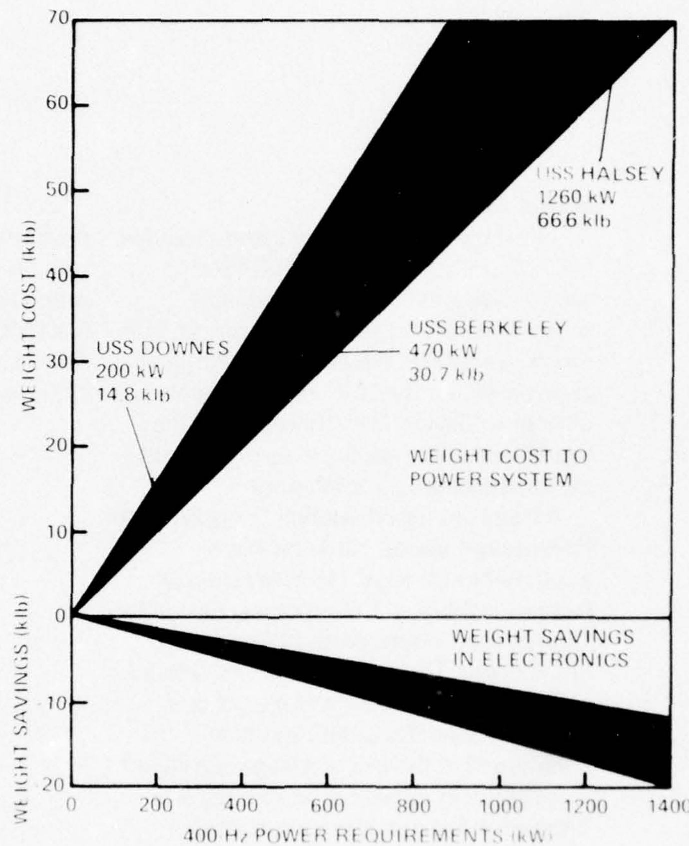
The weight penalty is always much more than the weight savings when *400 Hz* is used aboard a ship. A comparison of the penalty versus savings is shown for various 400-Hz power requirements.

The curves were obtained by first plotting minimum and maximum data points of both weight savings and penalty, at a power requirement of 200 kW. Because higher power requirements were assumed to require proportionately more weight, the curves were extrapolated as straight lines. The minimum weight savings line was obtained from the weights of two 100-kVA transformers. The maximum weight savings line represents mixes of smaller transformers, filters, and other electronic components. Plotted points for both weight penalty curves show the combined weights of two 100-kW MG sets. The minimum curve reflects the weights of the lighter (MIL-M-19160C) MG sets; the maximum, the heavier (MIL-M-19633B) MG sets. (The two MG specifications are *shown in parentheses.)*

Specific MG weight data for three ships is plotted to validate weight cost curves. USS DOWNES requires 200 kW of 400-Hz power; its MG sets weigh 14 800 lb (6.7 Mg). USS BERKELEY supplies 470 kW of power with 30 700 lb (13.9 Mg) of MG sets. And USS HALSEY can supply 12 600 kW of 400-Hz power with its 66 600 lb (30 Mg) of MG sets. These diverse examples are well within the range of the general weight penalty curves.

The assumption that using 400-Hz electronics saves shipboard weight is invalid. In fact, when 400-Hz power is used for electronics on ships having 60-Hz primary power, from four to ten times as much weight is added to the ship as is saved in electronics equipment.

## SHIPBOARD WEIGHT COST VERSUS WEIGHT SAVING USING 400-Hz POWER INSTEAD OF 60-Hz POWER



### *Reliability*

Since the 400-Hz power system requires 60-Hz input for operation, 400-Hz ship service power is always a less reliable source than 60-Hz ship service power. How much less reliable depends on frequency changer failure rate. MG sets have a history of poor reliability. They ranked 73 in the top 300 problem equipments of the Navy during a recent 12-month period.

A Navy 3M report entitled "Logistic High Failure Equipment" ranks problem equipment with regard to maintenance factors—actions, ship's reporting data, total failures, man-hours, parts, deferrals, and hours down. The overall ranking is arrived at by giving equal weight to each factor. The poor reliability of MG sets has contributed to the use of a large number of them either in parallel or as standby sets. This redundancy insures continuous availability of 400-Hz power, but at a high price.

Solid-state frequency changers (SSFCs) perform the frequency changing function with no moving parts and are therefore potentially more reliable and maintainable than MG sets. Replacing MGs with SSFCs should improve the reliability of frequency changers.

## RELIABILITY COSTS

### RANK OF 60-400-Hz MG SETS IN TOP 300 PROBLEM NAVY EQUIPMENTS 12/74 - 11/75

| FACTOR | DATA VALUE | FACTOR RANK |
|---|---|---|
| Maintenance actions — completed & deferred | 714 | 77 |
| Ships reporting maintenance data | 362 | 43 |
| Ratio of maintenance action to ships | 2 | 301 |
| Total failures status codes 2 or 3 — nonoperational or reduced capability | 376 | 71 |
| Man-hours (thousands) | 10 | 67 |
| Cost of parts (thousands) | 62 | 297 |
| Deferrals — both parts & assistance outside ship | 215 | 62 |
| Hours down (thousands) | 923 | 57 |
| Overall rank | | 73 |

### ***Interaction***

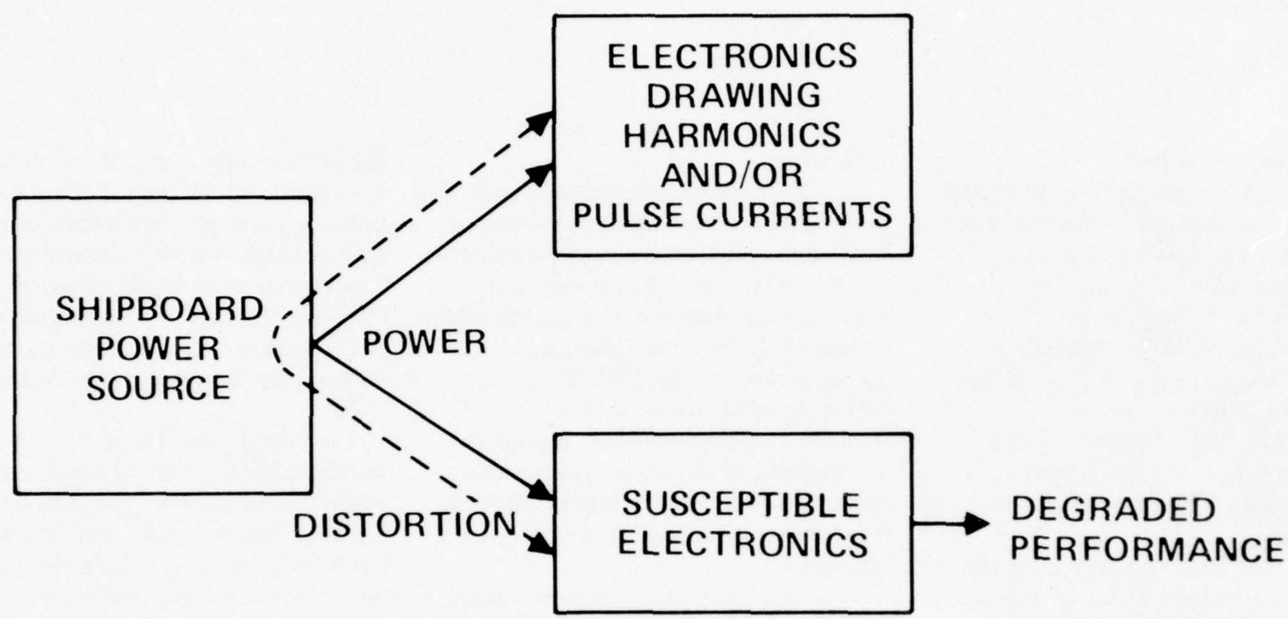
Many shipboard MG sets are dedicated to single electronic loads to preclude interference that occurs between loads fed by a common MG. Such interference can be caused by one load creating powerline distortions which degrade the performance of other susceptible loads. Harmonic or pulse currents drawn by loads cause voltage drops across the source impedance, generating corresponding harmonic or modulating voltages in the entire power system.

The Navy has conducted many shipboard tests to investigate, identify, and take corrective action on these 400-Hz electrical interference problems. Test teams from NAVSEC, Philadelphia, NSWSES, Port Hueneme, Calif., and NSRDC, Annapolis have extensively tested 400-Hz power-system and weapon-system interfaces on Navy ships and have found that large nonlinear and pulsating electronic equipment sets are the major loads responsible for interference problems.

The source impedance of shipboard 400-Hz generators is greater than that of 60-Hz generators primarily because the former have lower kilowatt ratings. (Shipboard 400-Hz power requirements are only about one-tenth those of 60-Hz power.) In addition, 400-Hz system impedance is somewhat higher because of the higher reactance of the power distribution lines. The result is higher harmonic and modulation voltages on 400-Hz systems for equal distortion currents.

Impedance and coupling problems are greater for 400-Hz systems than for 60-Hz systems. Dedicated MG sets are commonly used to reduce impedance coupling. The mechanical inertia of the MG set acts as an *integrator or low-pass filter.* This serves both to protect the power source from load transients and to protect the load from power-source transients. An MG set will also isolate load harmonic currents from *the source, thereby acting as a harmonic* current filter. MG sets are often dedicated to specific equipments to serve this filtering function.

## LOAD INTERACTION



### *Improvement Projects*

The Navy has been trying to solve 400-Hz power-system problems for many years. To strengthen and coordinate some of these efforts, NAVSEC began a program in June 1973 called "Improvement of 400-Hz Power System and Weapon Systems Interface." Various aspects of this program are described below.

Design improvement studies were performed to improve MG response to pulsating loads. This effort was found to be unpromising.

Since better line filters would eliminate some of the needs for MG sets, actions have been taken to obtain better passive and active filters. NSRDC has developed an energy storage unit (ESU) passive filter, and a brassboard model of it has been tested on several ships. NAVSEC has contracted to develop an active filter. The current filter design is deficient at higher frequencies and must be made smaller and lighter.

Extensive shipboard studies showed that better test equipment and methods were needed to define power-system problems. Consequently, NSRDC developed a portable solid-state dynamic load simulator having nonlinearity and pulsing characteristics of major 400-Hz loads. NELC developed a better test methodology which determines the susceptibility of electronic equipment to powerline anomalies such as modulation, harmonics, and variations of voltage and frequency.

A working group of representatives from both Navy and industry was formed for the purposes of a) establishing electronic and weapon system design criteria, b) modifying specification requirements, and c) serving as a technical group for the interchange of 400-Hz power-system information and problems.

The solid-state frequency changer (SSFC) alleviates some of the problems associated with MG sets. Solid-state frequency changers are beginning to replace shipboard MG sets and can be expected to totally replace them in time. However, the inherent filtering capability of the MG set as a result of rotor mechanical inertia is not necessarily provided by the SSFC.

The Navy is developing a family of standard SSFCs. A three-phase program that will result in prototype units is nearing the end of the second phase. The program has been planned to reduce life cycle costs by avoiding the many problems of reliability, maintenance, logistics, and training that are associated with MG sets. However, the specifications indicate only a slight advantage in weight, volume, and power loss over comparably rated MG sets.

## Projects to Improve 400 Hz Systems

- Redesign MGs
- New filters
  - Passive
  - Active
- Better testing
  - Special equipment
  - New methodology
- 400 Hz working group
- Solid state frequency changers
  - Navy's standard

### *Future Trends*

Will future costs of 400-Hz systems increase or decrease? The results of extensive studies and shipboard tests indicate small hope of making MG set improvements that will lower their costs. Although not yet demonstrated, the design goal is to lower life-cycle costs by replacing MG sets with solid-state frequency changers (SSFCs).

Unfortunately, the proportion of 400-Hz electronics on Navy ships is increasing. If this trend continues, the costs to the Navy will rise considerably rather than decrease, even if MG sets are replaced by SSFCs. The electronic manufacturer's rationale for using 400 Hz has long been the size and weight advantage.

The impact of this increasing trend toward 400-Hz electronics is a continuing Navy requirement for more and more shipboard frequency changers and a continuing rise in associated maintenance and operation costs. New ships will need proportionately more space reserved for frequency changers and will have to be designed to carry their additional weight. Load interaction problems will become more severe as more 400-Hz loads are added.

# FUTURE

TRENDS

- INCREASING USE OF 400 Hz

UNLESS TREND REVERSED

- MORE FREQUENCY CHANGERS
- MORE ACQUISITION, MAINTENANCE, AND OPERATING COSTS
- MORE SHIPBOARD SPACE AND WEIGHT REQUIREMENTS
- MORE LOAD INTERACTION PROBLEMS

***Cost Penalty Summary***

In addition to acquisition costs for frequency changers on surface ships, annual dollar costs are $2.4 million for fuel and $2.7 million for maintenance. Other costs are incurred in an effort to improve 400-Hz systems. The need for frequency changers has resulted in the installation of an average of four 60-Hz to 400-Hz MG sets on each of 383 surface ships. Four MG sets weigh an average of 19 200 pounds (8.7 Mg) and occupy an average volume of 240 cubic feet (6.9 $m^3$ ). MG sets have a high failure rate. They rank 73 in the top 300 Navy problem equipments. Load interaction problems are more prevalent with 400-Hz power systems than with 60-Hz power systems. But the current trend is to use more and more 400-Hz electronics despite these resultant high costs and system penalties.

## FREQUENCY CHANGER COST/PENALTY SUMMARY

- COSTS
  - ACQUISITION
  - MAINTENANCE
  - OPERATING FUEL
  - IMPROVEMENT PROGRAMS
- SYSTEM PENALTIES
  - SIZE AND WEIGHT
  - RELIABILITY
  - LOAD INTERACTIONS
- FUTURE TRENDS

## Historical Reasons for 400-Hz Power

For many years the designer of shipboard electronic systems has had the choice of specifying either 60- or 400-Hz input power for specific equipment. During these years the available components and technology allowed him to achieve a smaller and lighter electronic system by specifying 400-Hz input power, because 400-Hz transformers, motors, generators, synchros, and filters are all lighter and smaller than their 60-Hz counterparts. A 400-Hz 50-kW transformer, for example, is 345 pounds (155 kg) lighter than a 60-Hz 50-kW transformer.

The problem with that approach is that the basic shipboard power source is generally a 60-Hz generator. Equipment designed for 400-Hz power input therefore requires a frequency changer between it and the 60-Hz ship service generator. A 60-kW MG set can weigh from 3600 to 5900 pounds (1.6 to 2.7 Mg) depending on its regulation and line-balancing features. For redundancy, a standby unit often is installed. Thus "saving" 345 pounds (156 kg) by designing 400-Hz electronics equipment can add 3600 to 11 800 pounds (1.6 to 5.4 Mg) to the ship's electrical power system.

The realization of this severe weight penalty led to BUSHIPS Instruction 9600.15 of 21 January 1963, which set a policy prescribing the use of 60-Hz power in preference to 400-Hz power. The order of preference was incorporated in superseding specifications MIL-STD-761 followed by MIL-STD-1399, Section 103.

Unfortunately, two factors have worked against the success of the 60-Hz preference policy. First, as explained above, the weight cost of using 400-Hz power appears as a savings instead of a penalty when the trade-offs are made exclusively at the electronic system level. The overall penalty of using 400-Hz power does not appear until the trade-offs include the impact on the total ship. Second, the MGs used for frequency changers can serve as filters that smooth out line and load transients and harmonic currents. Although filters are sometimes necessary for operation of electronic systems aboard ship, the penalties involved in using MG sets for filters do not appear until the design trade-offs are taken above the electronic equipment level.

The following sections discuss transformer and filter weight and system-level versus equipment-level trade-offs in more detail.

## HISTORICAL REASONS FOR 400-Hz POWER

- Availability of choice
- Lighter and smaller magnetics and filters in load
- Ineffective preference policy
- Filtering action of motor generator sets

### *Transformer and Filter Weight*

Theoretically, the weight of a conventional transformer varies inversely as the ¾ power of frequency, provided flux density, current density, and other design parameters are held constant. (These parameters are seldom held constant, however, since they affect transformer losses, temperature rise, and regulation.) The 400-Hz transformers used aboard Navy ships are about 33 percent of the weight and 40 percent of the volume of 60-Hz transformers with the same kVA rating. Similar weight and size advantages occur for motors, generators, and synchros.

Line filters for 400-Hz systems are also smaller and lighter than those for 60-Hz systems. Theoretically, 60-Hz capacitors are 6.67 times heavier and 60-Hz inductors 4.14 times heavier than their 400-Hz counterparts. (Capacitor weight varies inversely with frequency; inductor weight varies inversely as the ¾ power of frequency.)

Where size and weight were important, the electronic system designer usually specified 400 Hz over 60 Hz if both were available, merely on the basis of the lighter-weight magnetics and filter. For example, a 50-kW 60-Hz transformer weighs 510 pounds (230 kg), whereas a 50-kW 400-Hz transformer weighs only 165 pounds (74 kg), a savings of 345 pounds (156 kg). The electronics designer took these equipment-level savings as an advantage, failing to consider the impact at the ship level.

# 60-Hz AND 400-Hz TRANSFORMER COMPARISON

REF: MIL-T-15108B (60 Hz)
REF: MIL-T-17221B (400 Hz)

| XFMR RATING kVA | XFMR WT | | WT RATIO | XFMR VOL | | VOL RATIO |
|---|---|---|---|---|---|---|
| | 60 Hz LB | 400 Hz LB | | 60 Hz $IN^3$ | 400 Hz $IN^3$ | |
| 1 | 30 | 18 | 0.43 | 525 | 335 | 0.64 |
| 3 | 65 | 25 | 0.38 | 1,020 | 470 | 0.46 |
| 5 | 90 | 30 | 0.33 | 1,450 | 600 | 0.41 |
| 7.5 | 116 | 40 | 0.34 | 1,910 | 800 | 0.42 |
| 10 | 145 | 50 | 0.34 | 2,250 | 870 | 0.39 |
| 15 | 206 | 75 | 0.36 | 4,000 | 1,750 | 0.44 |
| 25 | 280 | 105 | 0.38 | 5,700 | 2,150 | 0.38 |
| 37.5 | 396 | 140 | 0.35 | 7,500 | 2,750 | 0.37 |
| 50 | 510 | 165 | 0.32 | 10,025 | 3,775 | 0.38 |
| 75 | 695 | 240 | 0.35 | 13,000 | 4,575 | 0.35 |
| 100 | 950 | 310 | 0.33 | 17,200 | 7,100 | 0.41 |
| | | AVG | 0.36 | | AVG | 0.42 |

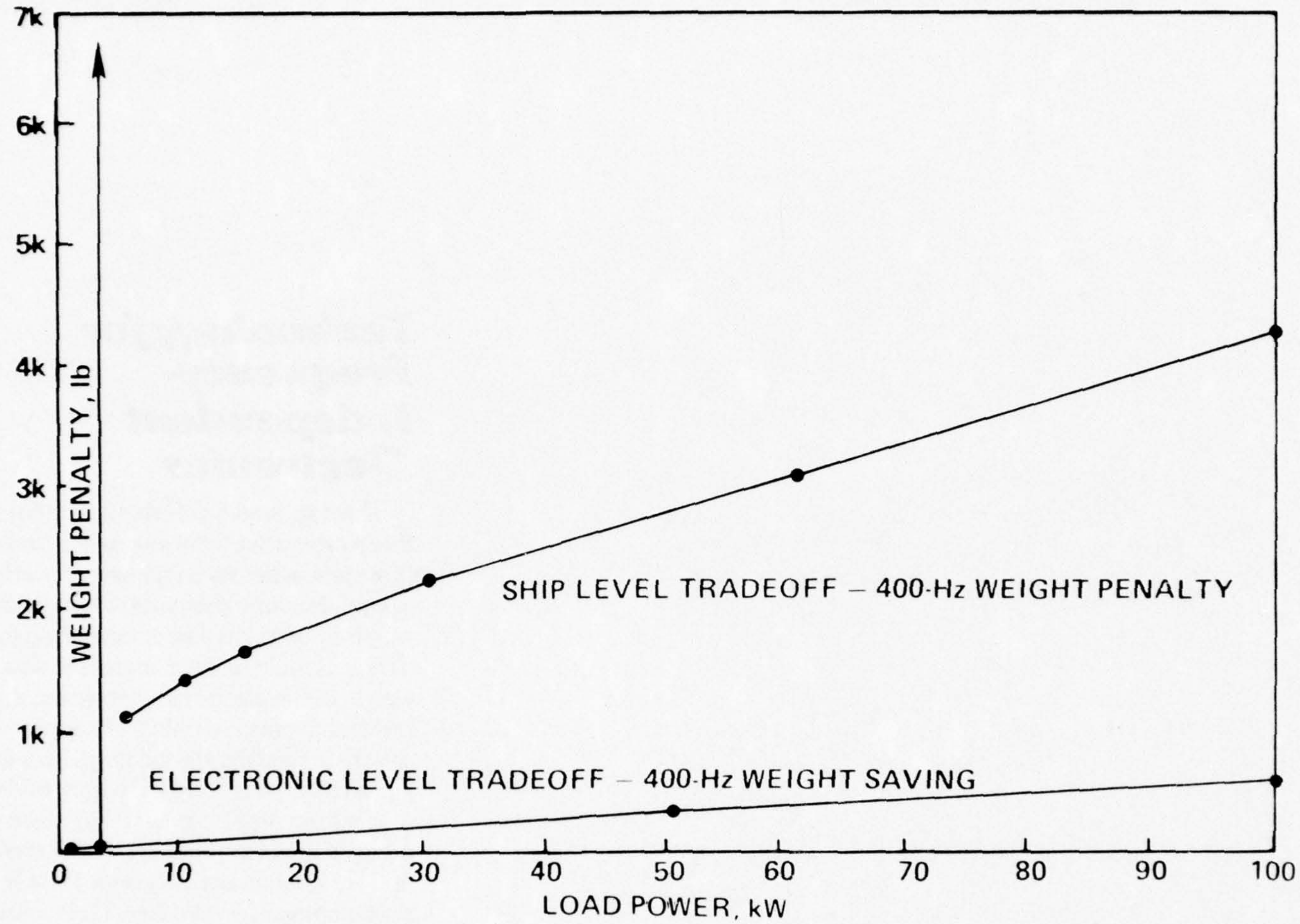
| | 60 Hz | 400 Hz |
|---|---|---|
| TEMP RISE | 80°C | 150°C |
| REGULATION | 2% | 1.5% |

### ***System Versus Equipment Trade-Offs***

The difference between making trade-offs at the electronic system level versus the ship level can easily be illustrated. The electronic-level trade-off shows the difference in weight between 60- and 400-Hz transformers as a function of load kW. A moderate electronics weight saving is achieved by specifying 400-Hz input power. The more realistic ship-level trade-off considers the weight of an MG set to provide 60- to 400-Hz conversion minus the weight saved in the electronics by using 400-Hz power. The trade-off at the ship level shows a substantial weight penalty in the total system (ship plus electronics) where 400-Hz input power is specified for electronic equipment.

The soundness of choosing 400-Hz power for electronics in ships with 60-Hz prime power is questionable even for conventional technology using 60-Hz magnetics. Recent advances in power electronic technology that eliminate the need for line-frequency magnetics, either 60-Hz or 400-Hz, further support the specifying of 60 Hz for electronics on 60-Hz ships.

## 400-Hz VS 60-Hz WEIGHT TRADE OFF VS LOAD kW



## Technology for Frequency-Independent Electronics

The arguments presented so far indicate that a return to 60-Hz magnetics would provide a better total (ship-electronic) system than one using 400-Hz electronics with frequency changers, even though such a return would result in increased size and weight of the electronics. However, the preferable option would be to apply switching regulator technology. This would allow electronics to operate from 60-Hz power (and 400-Hz power) by means of power conversion circuitry that is smaller and lighter than conventional 400-Hz power conversion circuitry. This technology is discussed in detail next. The frequency dependence of electromechanical components is also discussed.

# TECHNOLOGY FOR FREQUENCY-INDEPENDENT ELECTRONICS

- Power conversion

  switching regulator technology

- Electromechanical components

### ***Switching Regulator Technology***

A technological revolution has taken place in recent years in the field of ac-to-dc and dc-to-dc power conversion. The technology responsible for this revolution is termed switching regulator technology. Advances in components and analysis techniques have been combined with new and old circuit concepts. Switching regulator technology has yielded increased efficiency (less power loss) and decreased size, weight, and cost of power-conversion equipments.

# SWITCHING REGULATOR TECHNOLOGY

***Power Supply Functions***

A power supply is essentially a buffer *circuit that matches a load to its power* source. The power source typically is a ship service turbine generator that provides 3 $\phi$ 60-Hz 450 Vac power as defined by MIL-STD-1399, Section 103. A common example of an electronic load is an equipment's 5 Vdc logic circuits. Almost all power in electronics is eventually used as dc power. A system design consideration is to minimize the impact of the power supply function on system figures of merit such as size, weight, reliability, source power, cooling requirements, and cost. Ideally, for a load compatible with the source, the power supply function would be served merely by interconnecting wires. Usually, the power supply function is more complex, requiring conversion and regulation of various electrical characteristics.

# POWER SUPPLY INTERFACES

| Power Source | Power Supply | Electronic Load |
|---|---|---|
| Shipboard systems (MIL-STD-1399) | A buffer element that matches load to source | Digital |
| Aircraft systems (MIL-STD-704) | | Analog |
| Shore systems | | Radar |
| Ordnance | | Sonar |
| | | ECM |

### *Power Supply Classes*

Power supply regulator circuits and power conversion circuits can be either dissipative or lossless. Dissipative regulators, by design, draw more power from the source than they deliver to the load. The undelivered power is converted to heat and removed by a cooling system. Familiar examples are the zener diode shunt voltage regulator and the transistor series voltage regulator.

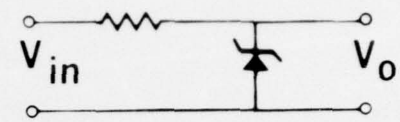
In lossless regulators, the power delivered to the load equals that drawn from the source. Neither the regulation nor *the conversion function, by itself, absorbs* power. Power "losses" (conversion to heat, which is wasted) are caused by less than ideal components. Examples of lossless regulators are ferroresonant transformers and switching regulators.

Switching regulators using semiconductor switches have been used since the 1950s. They were commonly applied in many aerospace applications in the 1960s and became well established in commercial application in the early 1970s. Of the various types of switching regulators, those that are proving most useful operate from dc input power, obtaining the dc by direct (no transformer) rectification of the ac lines if the power source is ac. Power conversion is then accomplished by off-on modulation of a semiconductor switch operating at higher than normal powerline frequencies. Modulation is usually in the 10-100 kHz range. This technology can provide power conversion equipment that *is independent of powerline frequency.*

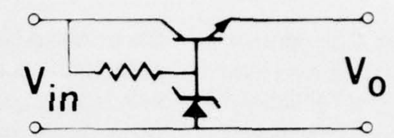
## POWER SUPPLY CLASSES

- Dissipative Regulators

  Shunt example

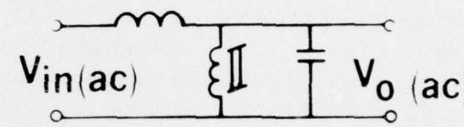



  Series example



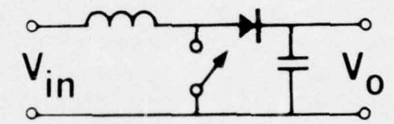

- Lossless Regulators

  Ferroresonant example

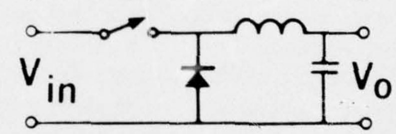



  Switching examples

  Shunt (flyback)




  Series



### ***Switching Mode Power Conversion***

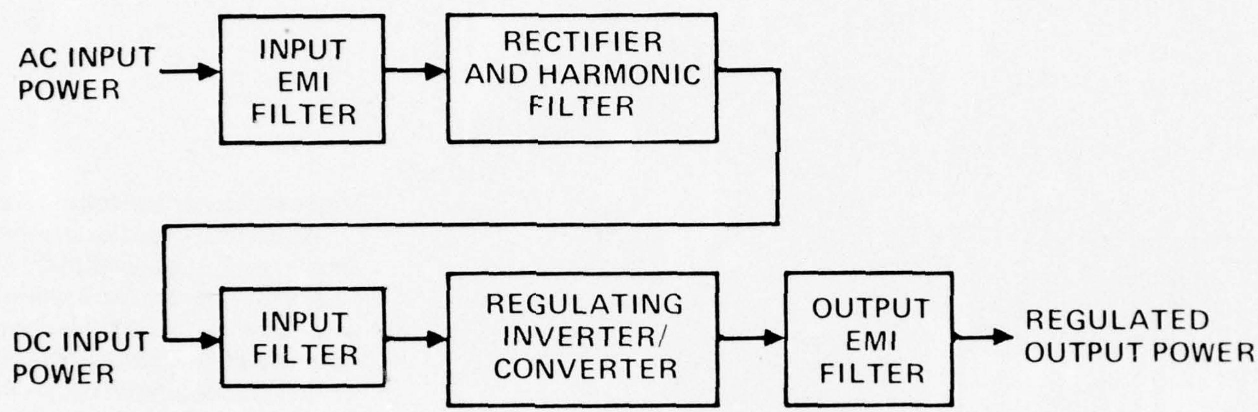
A typical block diagram of a switching regulator consists of an input *EMI filter*, a rectifier and (if needed) harmonic filter, an input filter, an inverter/converter that provides power conversion and regulation, and an output EMI filter.

Consider the frequency dependence of each block. The input EMI filter is designed to attenuate high-frequency noise caused by the switching of power semiconductors in the unit. Its size and weight are independent of the powerline frequency. The size and weight of the rectifiers are also independent of powerline frequency. With present technology, both size and weight of harmonic filters are functions of powerline frequency—60-Hz filters are four to six times heavier and larger than 400-Hz filters. At the output of the rectifier, the power is dc. If the switching regulator operates from a dc power source, power is brought into the circuit just ahead of the input filter, and the previous blocks are not used. This dc point in the circuit, sometimes called a dc *link, is an advantage if uninterruptable* power is a system requirement. The input filter is designed to attenuate the noise at and above the fundamental inverter/converter switching frequency. Its size and weight are determined only by the inverter/converter design and are independent of powerline frequency. The inverter/converter design is the heart of the circuit. If the required output is ac, the circuit is a dc-to-ac inverter whose size and weight depend on the ac output frequency. Very little ac power is required in electronics. If the output is dc, the circuit is a dc-to-dc converter; its size and weight are independent of powerline frequency and depend on the state of the art of component, circuit, and packaging technology. The output EMI filter attenuates the high frequencies generated by the switching elements of the circuit, and its size and weight are independent of powerline frequency.

The only component in the system whose size and weight depend on powerline frequency is the harmonic filter. If harmonic current suppression to protect the power source is not required, switching regulator size and weight depend only on output power and technology, rather than whether the unit is designed for 60- or 400-Hz use.

Switching regulators have substantial advantages over their dissipative counterparts.

## SWITCHING MODE POWER CONVERSION



***Advantages of Switching Regulators***

A switching regulator is ½ to ⅙ as large and ⅓ to ⅙ as heavy as its 60-Hz dissipative counterpart. It is also smaller and lighter than its 400-Hz dissipative counterpart. Its relatively high efficiency, from 65 to 95 percent, means that for a given load power, little additional power is drawn from the platform power source to be dumped as heat into the platform cooling system. Unlike a dissipative regulator, its efficiency remains high over wide variations in input voltage. Because of these significant advantages, switching regulators are being increasingly used, even in shipboard equipments with 400-Hz input power. These advantages are even more significant when the comparisons are made at the system level.

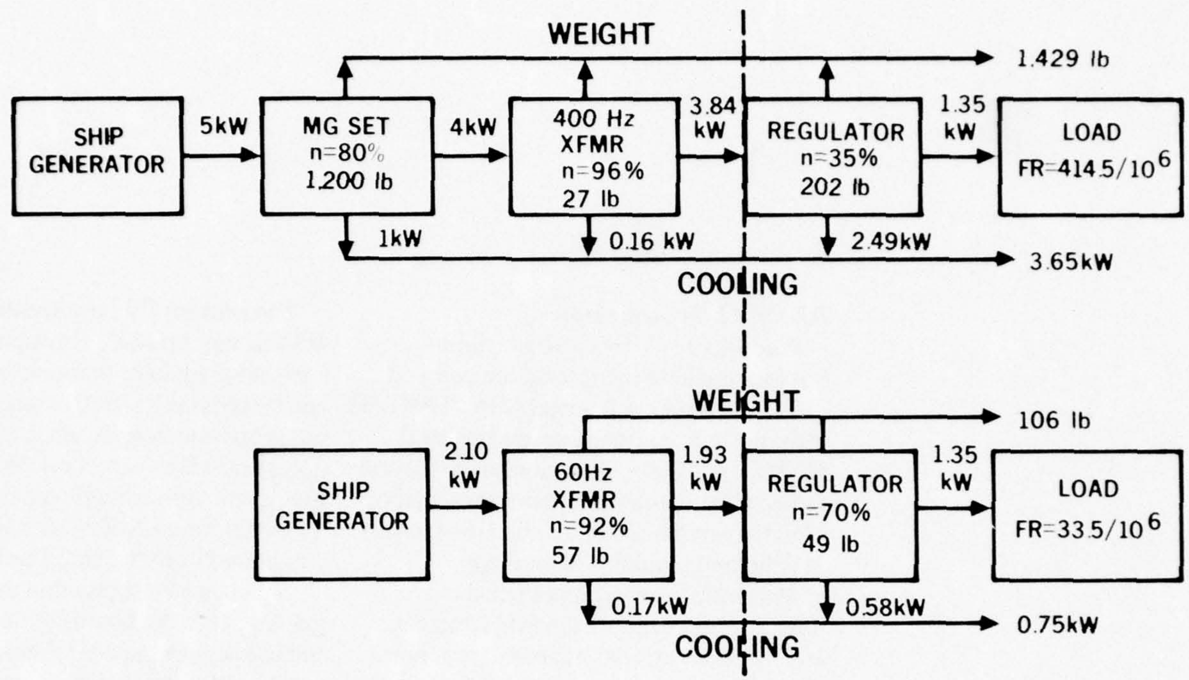
# ADVANTAGES OF SWITCHING REGULATORS

- Smaller size (2 to 6 times smaller)
- Lighter weight (3 to 6 times lighter)
- Accepts wide input voltage variation (up to 10:1)
- High efficiency (65 to 95%)
  - Reduced power from source
  - Reduced cooling required

### *System Level Advantages*

A common shipboard practice has been to specify 400-Hz input power for electronic equipment, to minimize the weight of its magnetic components. This requires the use of a frequency changer such as an MG set to convert from 60- to 400-Hz power. Dissipative regulators are then commonly used to provide regulated power for the electronics. The upper block diagram reflects this configuration. For 1.35 kW of power delivered to a 5 Vdc digital load, 5 kW of power is required from the source, 3.35 kW is dumped into the ship's cooling system, and the weight of this "power supply" (the components between the load and the power source) is 1429 pounds (640 kg). The failure rate of this type of power supply is typically 414 per million hours. These figures are based on data shown for standard military specification power supplies from a vendor's catalog. Using military specification switching regulator power supplies from the same vendor's catalog, the need for a frequency changer is eliminated and the results are shown in the lower block diagram. For the same 1.35-kW load, power required from the source is only 2.1 kW, power dumped into the cooling system is only 0.75 kW, the weight of the power supply is only 106 pounds (48 kg), and the failure rate is only 33.5 per million hours. Compared with the newer switching regulators, the standard power system is 13.5 times heavier, draws 2.4 times more power from the source, dumps 4.9 times more power into the cooling system, and has 12.5 times greater failure rate. This study shows the system leverage achieved through the use of switching regulator power supplies. What happens in a specific equipment example?

# SYSTEM IMPACT OF SWITCHING REGULATORS - SHIPS




← ELECTRONIC/ELECTRICAL SYSTEM INTERFACE

## Improvement

| | |
|---|---|
| • WEIGHT | 13.5 |
| • POWER FROM SOURCE | 2.4 |
| • POWER INTO COOLING SYSTEM | 4.9 |
| • RELIABILITY | 12.4 |

### *AN/SPG-51 Redesign*

Radar Set AN/SPG-51 is a pulse doppler tracking radar used for gun and missile fire control. It is part of the TARTAR missile system widely used on U.S. and NATO ships. The contractor has proposed redesigning the pulse transmitter and the CWI transmitter to exploit the advantages of switching regulator technology.

Presently the six-cabinet pulse transmitter operates from 60-Hz power, and its power conditioning equipment is housed in two cabinets. Redesigned to use switching regulator technology, the power conditioning equipment can be packaged in the spare space within a transmitter cabinet, eliminating two of the six cabinets heretofore used for the pulse transmitter. Transmitter weight can thus be reduced by 58 percent, floor space by 30 percent, and power consumption by 12 percent. At the same time, its reliability will increase by 40 percent.

The present CWI transmitter requires 400-Hz input power. Through the use of switching regulator technology, the weight can be reduced by 350 pounds (158 kg); but more significantly, since it will then accept 60-Hz power, three MG sets and their controllers, weighing a total of some 11 000 pounds (4.95 Mg), can be eliminated from the ship's power system.

This example shows that the leverage gained in system figures of merit through the use of switching regulators is proving true in redesigns of actual equipment.

## AN/SPG-51 RADAR

| PULSE TRANSMITTER | PRESENT | PROPOSED | IMPROVEMENT |
|---|---|---|---|
| CABINETS | 6 | 4 | 2 |
| Weight (lbs) | 11,220 | 4,680 | 6,540 |
| Space ($ft^2$) | 68.3 | 48.0 | 20.3 |
| Power (kW) | 52.9 | 47.0 | 5.9 |
| MTBF (hrs) | | | 40% |

CWI TRANSMITTER

- Slightly lighter
- 60 Hz operation
- mg set eliminated

### Loads

Electronics technology tends toward the increasing use of digital processing and control techniques. And in digital processing, the use of memory elements is increasing. As an example, system equipment interconnections are being designed as serial data transmission lines, which provide lower cabling weight and complexity and permit greater functional redundancy. The required parallel-to-serial conversion for serial data transmission require memory elements, but digital systems with memory are very sensitive to transient power losses. For these systems, recovery software and hardware must be used to correct errors and to preserve and reconstruct memory.

Switching regulators, because of their energy storage elements and ability to operate over a wide range of input voltage, provide transient-free output power in spite of input transients that would propagate through dissipative regulators. The higher output ripple of switching regulators is well tolerated by both bipolar and MOS digital circuits.

## SYSTEM IMPACT OF SWITCHING REGULATORS - LOADS

Increasing Use of Digital Processing with Memory Elements

- Transient loss of power requires recovery software to
  - Correct errors
  - Reconstruct memory
- System can tolerate higher noise level
  - Error propagation differs from analog systems
  - Components specified for noise rejection
  - Load induced noise quite high
  - Clocked operation

Switching regulators match new load

- Operate over wide range of input voltages
- Higher output ripple tolerated by load

### *Product Line Trend*

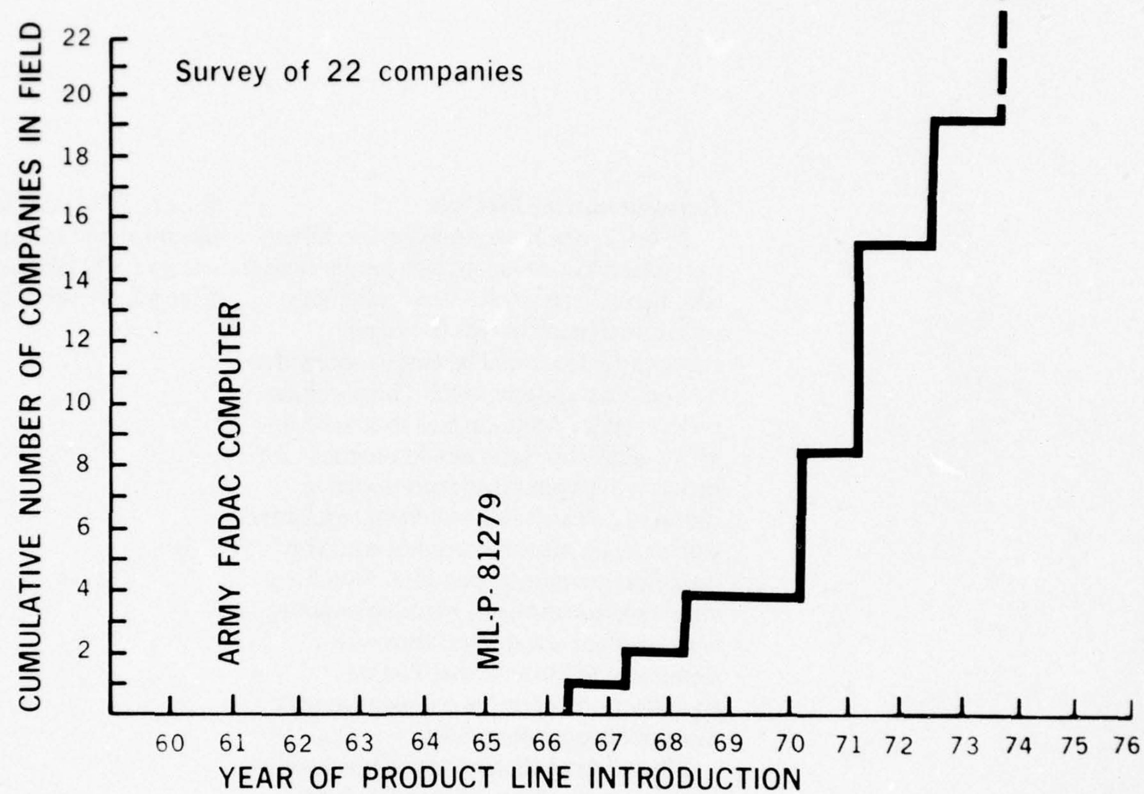
That switching regulators are advantageous in systems is reflected by their appearance in more and more company product lines.

In an early military application, switching regulators were used in the power supplies for the Army FADAC computer, which used germanium power transistors in a pulse-width modulated regulator operating at 1.2 kHz.

In 1965 the Navy sponsored the development of the MIL-P-81279 power supplies, a family of 20-kHz switching regulators and dissipative regulators designed for operation from aircraft 400-Hz power. These power supplies are still being produced and sold.

In 1966-1967, low-cost power transistors capable of switching at 20 kHz became available, and switching regulators were introduced, as a standard item, into the commercial power supply market. In 1972-1973 a survey of the major power supply vendors—including all of those with annual sales over $2 million—indicated that all but three either had a standard switching regulator product line or planned to have one by the end of 1973. A 1974 market survey found 1000 to 1400 companies in some phase of manufacturing power supplies, 200 to 300 of them selling to noncaptive markets. Today (1976) most power supply manufacturers probably have switching regular power supplies available in their product lines.

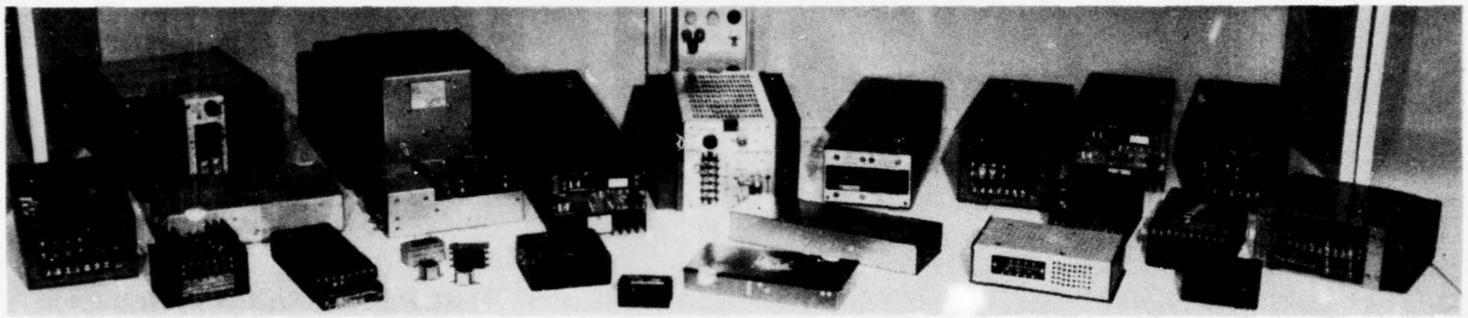
# SWITCHING REGULATOR PRODUCT LINE TREND

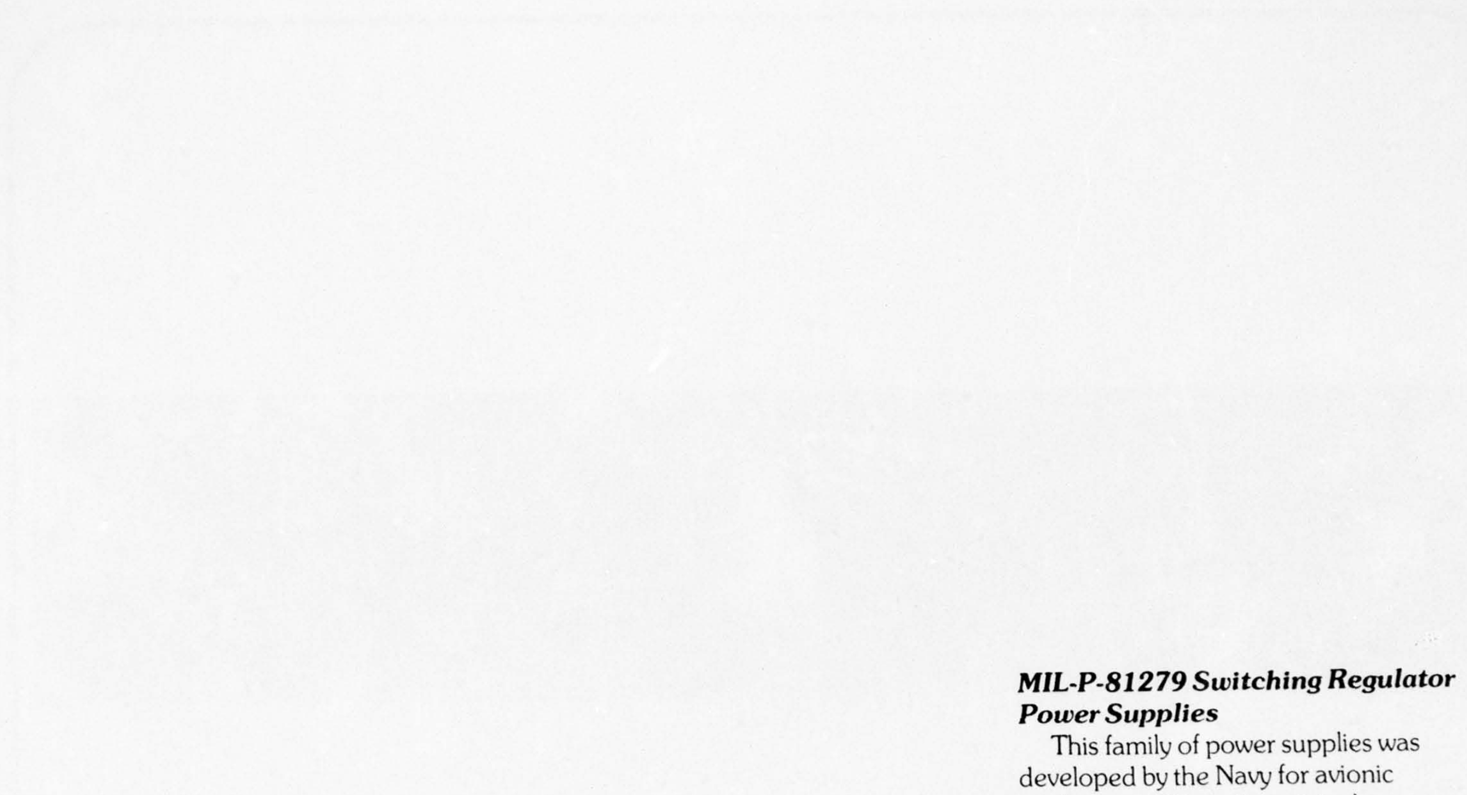


***Representative Models***

In 1972, one representative model was purchased from every power supply vendor who had as a standard item a switching regulator that either was frequency independent or could be easily modified to be frequency independent. The purchase orders totaled less than $12 thousand. In 1976, $250 thousand would probably not be enough to purchase representative models of all available switching regulators with circuit configurations that could be made frequency independent. Switching regulators are available in today's market because their advantages created a demand and because they can be manufactured at prices competitive with dissipative regulator prices.

Most of the switching regulators used in Navy equipment are either militarized standard designs or custom designs. Characteristics of several switching regulators being used in the Navy are shown. Of interest is their wide range of electrical output capabilities—from a few watts to 300 kilowatts in a single unit, and from a few volts to several kilovolts.





***MIL-P-81279 Switching Regulator Power Supplies***

This family of power supplies was developed by the Navy for avionic applications. Since the original development in 1965, the family has been used for Air Force, Navy, Army, and commercial applications. The family contains both dissipative and switching regulator members. The switching regulators, as shown, range in output power from 7.5 to 60 watts. A 400-Hz transformer at the input restricts the operation to 400-Hz sources, although large 60-Hz commercial versions are available.

# MIL-P-81279 SWITCHING REGULATORS

## INPUT POWER: 3$\phi$ 115 V/200 V 400 Hz

| Slash Sheet | Voltage | Current | Power |
|---|---|---|---|
| | V | A | W |
| 2 | 3 | 5 | 15 |
| 4 | 6 | 5 | 30 |
| 6 | 12 | 5 | 60 |
| 7* | 1.5 – 6 | 5 | 7.5 – 30 |
| 8* | 3 | 5 | 15 |
| 9* | 6 | 5 | 30 |
| 10* | 6 | 15 | 90 |
| 11* | 12 | 5 | 60 |
| 12** | 28 and 28 | 2.5 | 60 and 60 |

* Requires power module for input

** Power module: 3$\phi$ 115 V/200 V 400 Hz to 28 Vdc

***AEGIS Switching Regulator Power Supplies***

A family of standard switching regulator power supplies was developed for the AEGIS AN/SPY-1 radar signal processor. Input power is 3 $\phi$ 115-V 400-Hz Type I power per MIL-STD-1399, Sec 103. However, the basic circuit (less EMI filter and circuit breaker) will operate from dc, 50-Hz, 60-Hz, and single-phase power. Output power of a single unit ranges from 100 to 300 watts. Up to four units can be used in parallel for 1200 W output. Special characteristics include redundancy features that provide uninterrupted bus power in the event of a power supply failure.

## AEGIS AN/SPY-1 RADAR LOW-VOLTAGE POWER SUPPLIES

| Model | Output Voltage | Output Current | Output Power | Size and Weight |
|---|---|---|---|---|
| | V | A | W | |
| 900 | 5 | 60 | 300 | A |
| 901 | 5 | 25 | 125 | B |
| 902 Dual | 5 and 5 | 10 and 10 | 50 and 50 | B |
| 902 | 10 | 10 | 100 | B |
| 903 Dual | 5 and 12 | 10 and 10 | 50 and 120 | B |
| 903 | 18 | 10 | 180 | B |
| 904 | 25 | 10 | 250 | B |

| | Size | Weight |
|---|---|---|
| A | 17" x 4.54" x 5.22" | 16 lb |
| B | 8.5" x 4.54" x 5.22" | 8 lb |

Input power
3$\phi$, 115 V, 400 Hz

***AN/BQQ-5 and AN/BQQ-6 Switching Regulator Power Supplies***

A family of switching regulator power supplies was developed for the AN/BQQ-5 and AN/BQQ-6 sonar equipments. Input power is ship service 3 $\phi$ 115-V 60-Hz power. However, the basic circuitry concept is frequency independent, and slight modifications allow operation from standard aircraft and shipboard ac power sources or from dc voltages obtained by rectification of those power sources. Single-unit power supplies have multiple output voltages with single output powers up to 350 watts. The power supplies are packaged in a configuration compatible with the Navy Standard Electronic Module (SEM) program modules. The basic circuit is used on several Navy, Air Force, Army, and NASA equipments.

## AN/BQQ-5 AND AN/BQQ-6 SONAR POWER SUPPLIES

- 14 TYPES
- 5 TO 90 V VOLTAGE RANGE
- 0.1 TO 70 A CURRENT RANGE
- SINGLE OUTPUT POWER TO 350 W
- INPUT POWER: $3\phi$, 115 V, 60 Hz

***Line-Independent Switching Regulator Power Supplies***

This family of switching regulator power supplies is based on standard 10-kHz SCR power conversion modules. A basic module operates from dc power obtained from rectified 115-V 60-Hz or 400-Hz ac power. The module inputs can be placed in series to operate from a 440 Vac source. The basic power level is 7 kW, but units can be paralleled to provide any desired output power. Output voltages can be as high as 50 kV. The module has beer used in Navy and Army equipments and is the basis of the Navy AN/SPG-51 redesign.

## LINE-INDEPENDENT POWER SUPPLIES (LIPS)

(AN/SPG-51 RADAR)

- 7-kW MODULES PARALLELABLE TO ANY POWER
- OUTPUT VOLTAGES TO 50 kV
- FREQUENCY-INDEPENDENT INPUT
  - $3\phi$
  - 115 V OR 440 V
  - 60 Hz OR 400 Hz
- SCR POWER SWITCHES
- 10 kHz SWITCHING FREQUENCY

***Mark 84 Frequency Changer***

This equipment is used to convert 60-Hz shipboard power to 400-Hz input for the AEGIS system on USS NORTON SOUND. The output power is ac rather than dc as in the previous examples. The conversion approach, however, is first to rectify input power to dc power and then to perform power conversion at frequencies independent of the input line frequency. The output power is 400 Hz, but the output could be designed to provide any frequency including dc. The output power of this unit is 300 kW.

## AEGIS MARK 84 SOLID-STATE FREQUENCY CHANGER

- INPUT : $3\phi$, 440 V, 60 Hz
- OUTPUT: $3\phi$, 440 V, 400 Hz, 300 kW
- SWITCHING PEGULATOR DESIGN USING POWER TRANSISTOR
- TECHNIQUE APPLICABLE TO DC OUTPUT VOLTAGES

### *Availability of Technology*

Switching regulators are nonlinear, discrete time, multiloop, multi-input feedback circuits having components with wide parameter variations. The components work at high stress levels. Early designs were made mostly by trial and error and by modification of previous designs. Systematic analysis and design techniques either did not exist or were unknown to the designers. That situation is rapidly changing and a strong technological capability is developing.

Power electronics courses covering the design principles of switching regulators are now taught in many universities, usually at the graduate level. These universities include Duke University, California Institute of Technology, University of Missouri, Purdue, University of Toledo, University of Toronto, Canada, and the Delft Institute of Technology, The Netherlands. Other universities are in the process of expanding into the power electronics area.

The aerospace industry has been the major user of switching regulator power supplies until recently, either designing them themselves or having them designed by custom power supply vendors. Aerospace cutbacks stimulated the flow of experienced design engineers into the engineering staffs of commercial power supply vendors. NASA has a substantial in-house capability in power electronics, but in-house capability in DoD is limited.

In order to better exchange technical information in the field, the IEEE Airospace and Electronics Group established the Power Electronics Specialist Conference (PESC) in 1970. That group meets annually and publishes proceedings. Over 300 specialists attend the conference each year. POWER CON, a commercially sponsored conference, was established in 1975 and meets twice a year. The organization sponsoring POWER CON also publishes a bimonthly trade magazine in the field titled *Solid State Power Conversion.*

Most of the published information on switching regulator design is in the form of articles in technical journals or in vendor literature. Information in book form is limited. To make up for the lack of information available in book form, NASA has sponsored the development of a 600-page *Power Electronics Design Guide* that will be available within a year.

Through the mechanisms discussed here, power electronics technology is being made generally available to the engineering community.

## Availability of Technology

- Universities
- Aerospace industry
- Custom power supply vendors
- Commercial power supply vendors
- NASA
- DoD
- Conferences
- Literature

### *Increasing Use of Switching Regulators*

More and more switching regulators are going to be used in Navy electronic equipment because

a. They have inherent advantages in size, weight, and efficiency.

b. They have a large beneficial impact on system figures of merit when their characteristics are properly exploited in system design.

c. They are becoming better understood and increasingly available as systems components.

## INCREASING USE OF SWITCHING REGULATORS

- Inherent Advantages
- Advantages Multiplied at System Level
- Increased Availability

**Potential Problems**

Do switching regulators have any characteristics that could cause system problems? The answer is yes. However, for each characteristic that is a potential problem there is a design approach to avoid the problem. System designers must understand switching regulator characteristics if they are to fully exploit their advantages while avoiding their potential problem areas.

## Potential Problems With Switching Regulators

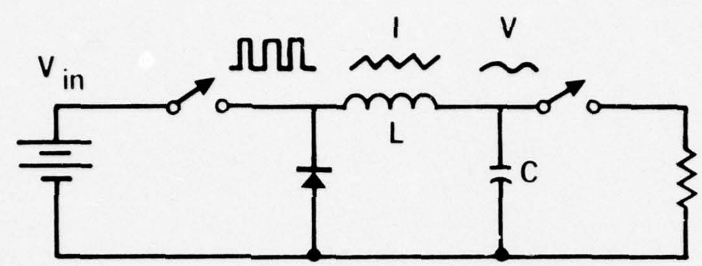
| Characteristic | System impact | Solution |
| --- | --- | --- |
| • Filter effects<br>Over shoot<br>Under shoot<br>Transient response<br>Ripple | Out-of-specification Voltages | Proper LC ratio<br>Proper circuit configuration |
| • Constant power<br>Input characteristic | System instability<br>Component failure<br>Inability to turn on | Proper interface analysis and control<br>Protection circuit |
| • High dI/dT, dV/dT | EMI problems | Careful layout and packaging<br>Proper component selection<br>Special circuit techniques<br>Filters |
| • Stability difficulties | System instability<br>Degraded performance | Two loop control<br>New analysis techniques |

### *Filter Effects*

If full-load or short-circuit current has been established in the inductor in the low-pass *filter of a series switching regulator* and the load is suddenly removed, the best the regulator can do is to open the modulation switch in the switching regulator. All of the energy (Energy = $I^2 L/2$) stored in the inductor ends up as energy (Energy = $V^2 C/2$) in the capacitor, and a voltage overshoot occurs. The overshoot voltage is the vector sum of the nominal output voltage and a voltage equal to the change in current times the *characteristic impedance* ($Z_O = \sqrt{L/C}$) of the output filter. For a fixed LC ratio (characteristic impedance), the percentage overshoot is greatest for low-voltage supplies such as 5 V logic supplies. Economic trade-offs often favor a large L and a small C. The resulting overshoot for a sudden load removal or the clearing of a short circuit can destroy bipolar logic circuits. Undershoot, transient response, and ripple are also affected by the selection of the LC values in the output filter circuit.

The engineering solution to these problems is to carefully select the proper values of LC. This has not always been done in the past. Unfortunately, some of the popular application notes that serve as a model for design have improperly selected values of LC. External overvoltage protection circuits are often used to protect against catastrophic overshoots. The preferred solution is proper selection of LC values in the filter section, with added circuitry to protect the device from catastrophic voltage overshoots that can occur under abnormal conditions.

# OVER SHOOT



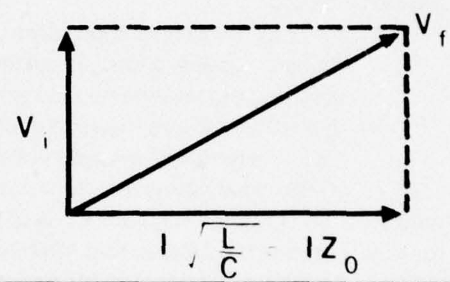

Prior to switch opening :

- Energy in inductor $= \frac{I^2 L}{2}$
- Energy in capacitor $= \frac{V^2 C}{2}$

After switch opening (final value) :

- All energy stored in capacitor

$$V_f = \frac{2E}{C}$$
$$= \left(V_i^2 + \frac{I^2 L}{C}\right)^{1/2}$$



## *Constant Power Input*

For a given output power, the input power of a switching regulator is constant. The input characteristic of a switching regulator is therefore a power hyperbola and the input current decreases as the input voltage increases. This behavior is opposite that of a resistive load, where input current increases as input voltage increases. The incremental input resistance $\triangle R$, is a negative resistance:

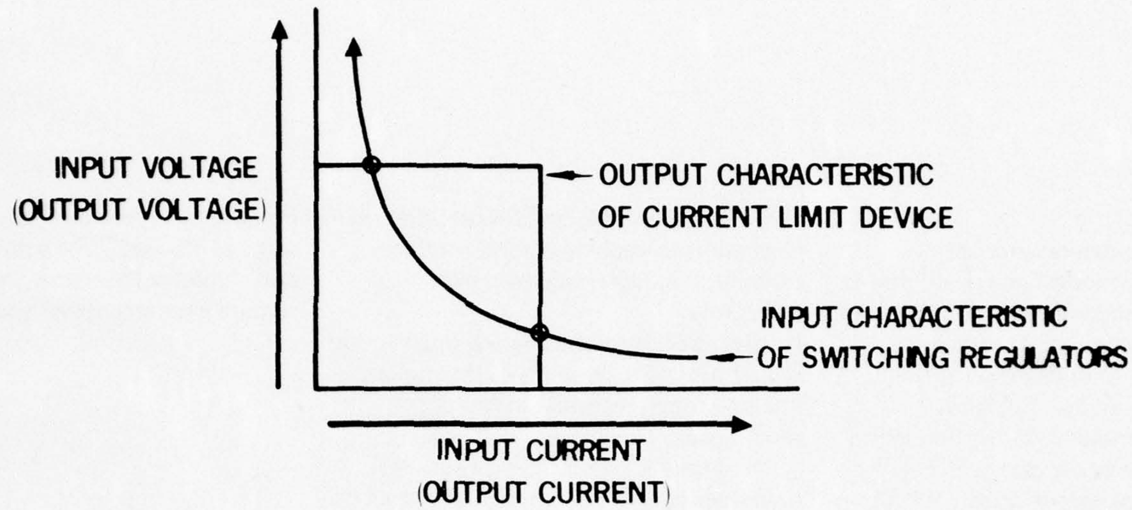
$$\begin{aligned} \triangle R &= dV/dI \\ &= d/dI\,(P/I) \\ &= -P/^2 \\ &= -V/I \\ &= -R. \end{aligned}$$

Because of this negative input impedance characteristic, a switching regulator (or any high-efficiency power conversion system) can be turned into a power oscillator by the addition of passive LC components, such as interconnecting cables or EMI filters, to the input. The engineering solution for passive components has been completely defined in Navy sponsored work completed in 1976 and reported in MIL-HDBK-241 and an IEEE paper. The negative input resistance can also affect other feedback systems such as ship service generators, MG sets, and solid-state frequency changers. This is a more complex situation, and a completely defined engineering approach must still be found.

Another potential problem with the constant power input characteristic is that as the input voltage goes to zero, the input current increases toward infinity. These high currents at low input voltages can destroy switching regulator components. The engineering solution is to add protective circuitry that inhibits destructive operation of the switching regulator at low voltages. It is interesting to note that military specifications require survival of electronic equipment through high-input-voltage regions but not through low-input-voltage regions.

A final potential problem occurs with the constant power input characteristic when it is combined with the current limiting characteristic of some power sources and some of the new solid-state power controllers. The turn-on trajectory of the switching regulator starts at low voltage and high current, with the desired stable operating point being the desired input voltage. If the trajectory wants to start in the region of current limitation, an undesirable stable operating point is reached on the current limit curve, and the desired operating point cannot be reached. The engineering solution is to have a protective circuit that inhibits low-voltage operation. The turn-on characteristics of the switching regulator must be closely coordinated with the current limit characteristics of any current-limited power source or solid-state power controller to be sure the turn-on trajectory is inside the current limit region.

# CONSTANT POWER INPUT




- Negative input resistance can cause power system instabilities
- Regulator can be destroyed by low input voltage
- Undesirable stable mode when operated from current limited source

### *EMI*

Switching regulators generate electromagnetic interference (EMI) due to *high rates of change* of current and voltage in the switching circuitry. To prevent switching regulator units from causing EMI, filtering all input and output leads is essential and packaging in an attenuating enclosure is usually necessary. Recent low-EMI designs have used a variety of EMI suppression techniques including

a. Control of transistor rise and fall times by adding external components rather than relying on inherent characteristics.

b. Use of soft recovery (but very fast) diodes.

c. Routing of all switched currents and their returns through twisted pairs or in mirror-image conductors on circuit cards.

d. Capacitive isolation of high dV/dt points in the circuit.

e. Use of lossy ferrites in balun and other line inductors.

f. Use of lossy Mylar dielectrics (rather than the conventional ceramic or mica dielectrics) in high-frequency filter capacitors.

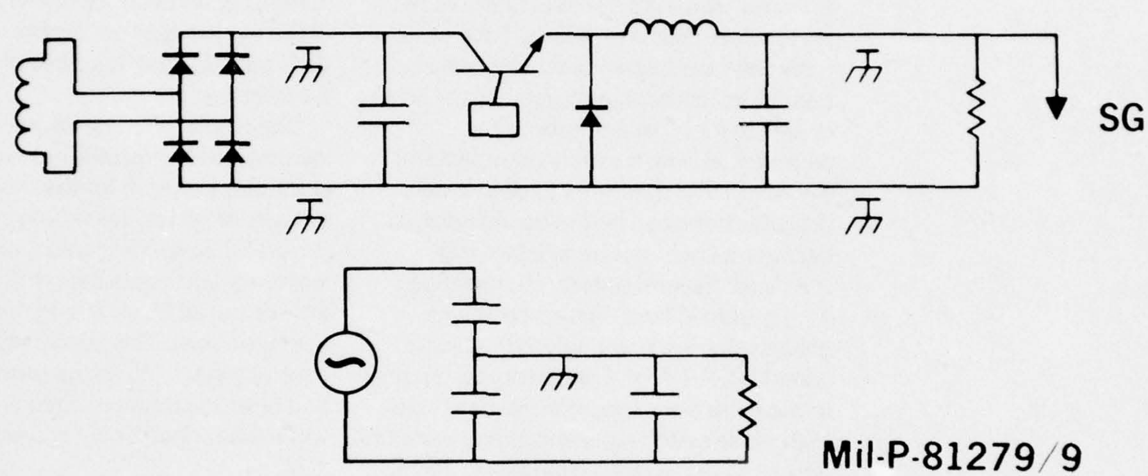
By means of these techniques, open-frame power supplies can be made that radiate less EMI than enclosed designs of the recent past.

Care must be taken that EMI control measures effective at the regulator level do not cause system problems. An example of such a problem can be demonstrated by connecting a MIL-P-81279/9 power supply into a system as a negative regulator. (There is no problem when it is used as a positive regulator.) In systems having the signal ground and chassis ground tied together at some point, feedthrough capacitors on the input of the switching regulator act as a capacitive divider that bypasses the regulator and feeds input noise to the load through the chassis. Sneak paths such as this are often difficult to locate and are probably the cause of many system problems caused by power source "glitches." The solution is to find and eliminate the sneak path rather than require a perfect power source.

# EMI PROBLEM

- Switching regulators are rich EMI Sources
- Methods of EMI control effective at regulator level can cause system problem.

Example Problem




Mil-P-81279/9

### *Stability*

Switching regulators are nonlinear, discrete time, multi-feedback loop, multi-input control systems operating in a high-noise environment. Several of the circuit parameters critical to stability have wide parameter variations. Stabilizing switching regulators has been as much a black art as a science for most designers. One commercial power supply manufacturer stated in 1972 that one out of four new designs attempted had to be abandoned because it could not be satisfactorily stabilized. Several stability characteristics long observed by designers have been analytically described only in the past 3 years (1974-1976). Laboratory techniques to measure open-loop gain/phase in the high-noise switching environment were first described in the open literature in 1975. The means of avoiding these complexities has been either to use extremely conservative stabilizing techniques at a considerable cost in performance or to use marginally stable designs that cause system problems. Engineering solutions to these problems are rapidly being obtained, primarily from NASA-sponsored programs in industry and various universities. Much of the work is reported in *Proceedings of the Power Electronics Specialist Conference.*

The results of many efforts are being incorporated by NASA into an interactive computer program for the modeling and analysis of power processing systems (MAPPS). NASA has also developed a two-loop standard control module (SCM) that will control all 24 switching regulator circuit configurations. This absolutely stable control system will be the most-analyzed and best-documented circuit of its type when a handbook on it is completed, in 1977.

## STABILITY

- Nonlinear
- Discrete time
- Multiloop
- Multi-input
- High noise environment
- Wide parameter variations

## *Switching Regulator Technology Summary*

In summary, switching regulator technology makes it possible for electronic equipment to be independent of the frequency of the input power source. The design can be identical for any power source—dc, 60-Hz, or 400-Hz. Additional benefits include

a. Small size.

b. Light weight.

c. High efficiency (using little power from the source and requiring little cooling).

d. The ability to maintain efficiency and performance over a wide range of input voltages.

e. Low cost and high reliability in high-power-level configurations (the crossover occurring at about 500 W with present technology).

When these advantages are properly understood and exploited, substantial system benefits are obtained. Switching regulators have special characteristics, however, that must be considered in their design or application. Some examples follow. Filters must be designed to minimize the effects of overshoot, undershoot, poor transient response, and output ripple. System instabilities caused by the constant power input characteristic must be avoided. Protective circuitry must be added internally to the regulator to prevent damage at low input voltages. The interface with current-limited sources must be properly coordinated. Finally, the best design practices available must be used for EMI control and for the stabilization of feedback loops. These precautions are easily met by experienced switching regulator designers and users.

## Summary of Characteristics

Advantages Over Dissipative Regulators

- Frequency independent
- Smaller size
- Lighter weight
- Higher efficiency
  - Reduced power from source
  - Reduced cooling
- Accepts wide input voltage range
- Lower cost and higher reliability in higher power levels

Precautions

- Filter effects
- Constant power input characteristics
- EMI control
- Stability design

### *Electromagnetic Components*

In addition to power conversion circuitry, shipboard electronic equipment contains other components that are often frequency sensitive—circuit breakers, running time meters, fans, blowers, and other components. What impact do these have on designing for frequency independence?

## Frequency Dependence of Electromechanical Parts

- Circuit breakers
- Running time meters
- Fans and blowers

AD-A032 582 NAVAL ELECTRONICS LAB CENTER SAN DIEGO CALIF F/G 10/2

REDUCTION OF SHIPBOARD 400-HZ POWER REQUIREMENTS EXECUTIVE OVER--ETC(U)

OCT 76 J FOUTZ, E KAMM

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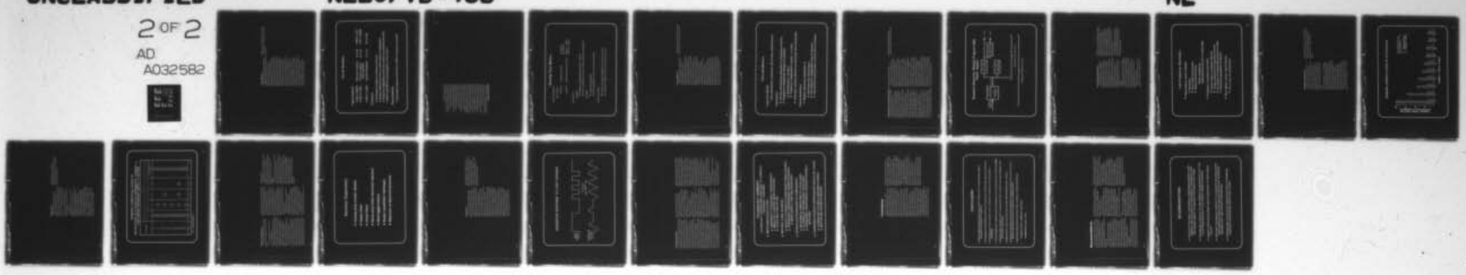


### *Circuit Breakers*

Shipboard circuit breakers identified in the *MIL-STD-242F selection* standard were studied through literature sources, specifications, and by contacting the manufacturers. All of the circuit breakers studied are frequency sensitive; even with factory modifications, they cannot meet full performance requirements at both 60 and 400 Hz. Theoretically, the performance requirements could be met by developing new electronic versions that would be similar to the new solid-state and hybrid power controllers. An R&D program would be needed to develop and qualify such equipment. Fortunately, in the present circuit breaker specification, the form and fit for both 60 and 400-Hz circuit breakers are identical for identical current ratings. Thus each electronic equipment, except for the circuit breakers, can be designed without regard for the power frequency, and either a 60-Hz or a 400-Hz circuit breaker of current design can be installed as appropriate, to match the power source of the ship.

# Circuit Breakers

**Types Considered**

| | | | |
|---|---|---|---|
| • MIL-C-39019 | *Miniature magnetic* | ac or dc | 0.05A to 20A |
| • MIL-C-17361 | Thermal-magnetic ABQ and NBQ | ac or dc | 10A to 1600A |
| • MIL-C-17588 | Hydraulic-Magnetic | ac or dc | 5A to 50A |

**Conclusions**

- All breakers studied are frequency sensitive
- Simple modifications will not make frequency independent
- Frequency independent electronic versions are possible with R&D
- 60 Hz and 400 Hz interchangeable in form and fit

**Recommendation**

- Use present breakers with 60 Hz or 400 Hz versions as required

### ***Running-Time Meters***

MIL-M-3971 covers dc and ac running-time meters. The dc version uses an inertia wheel driven by an escapement mechanism similar to that in a watch. While designed for dc, it will operate from ac power between 20 and 200 Hz. At higher frequencies there is insufficient time to wind the meter on a half power cycle. The mere addition of a rectifier to the meter would make it frequency insensitive. The ac versions use synchronous motors and are frequency sensitive. The 60- and 400-Hz versions have the same form and fit.

As with circuit breakers, present 60- or 400-Hz running-time meters could be installed as required in electronic equipment that is otherwise frequency independent. However, because it would be simple to develop a frequency independent running-time meter, it is recommended that this be done and that the present 60- and 400-Hz versions be used only in the interim.

# Running Time Meters

Types Considered

MIL-M-3971

| | | | |
|---|---|---|---|
| SLASH 1 | Escapement driven | 4-40 Vdc<br>40-130 Vdc | |
| SLASH 2 | Synchronous motor driven | 120 Vac<br>120 Vac | 60 Hz<br>400 Hz |

Conclusions

SLASH 1

- Frequency-independent dc and 20 – 200 Hz
- Minor modification to make totally frequency independent

SLASH 2

- Frequency dependent
- 60 Hz and 400 Hz are form and fit compatible

Recommendation

- Develop frequency-independent running time meter
- Use 60-Hz or 400 Hz versions as required in interim

### *Fans and Blowers*

Fans and blowers are covered by over 20 military specifications. They are all frequency sensitive. Frequency independent designs are possible, however, in either of two circuit configurations. In one, power is rectified to dc, and a dc drive motor is used to power the fan or blower. In the other, a frequency-independent inverter is used to power an ac drive motor. Either approach is more expensive than a conventional ac or dc motor drive.

Alternative cooling methods can eliminate the need for fans and blowers within the electronics. Present specifications assume 60-Hz prime shipboard power and require electronic equipment to use 60-Hz power for fans and blowers even if 400 Hz is used for the electronics. All of these approaches are satisfactory. The recommended approach is to let the manufacturer make the choice provided the equipment is frequency independent or can be procured to operate from the shipboard prime power source.

# Fans and Blowers

## Types Considered

Fans and blowers covered by 20 military specifications

## Conclusions

- All fans and blowers specified are frequency sensitive
- Frequency independent designs are possible
  - Rectification + dc drive
  - Frequency independent inverter + ac drive
- Alternate cooling methods can eliminate fans and blowers

## Recommendations

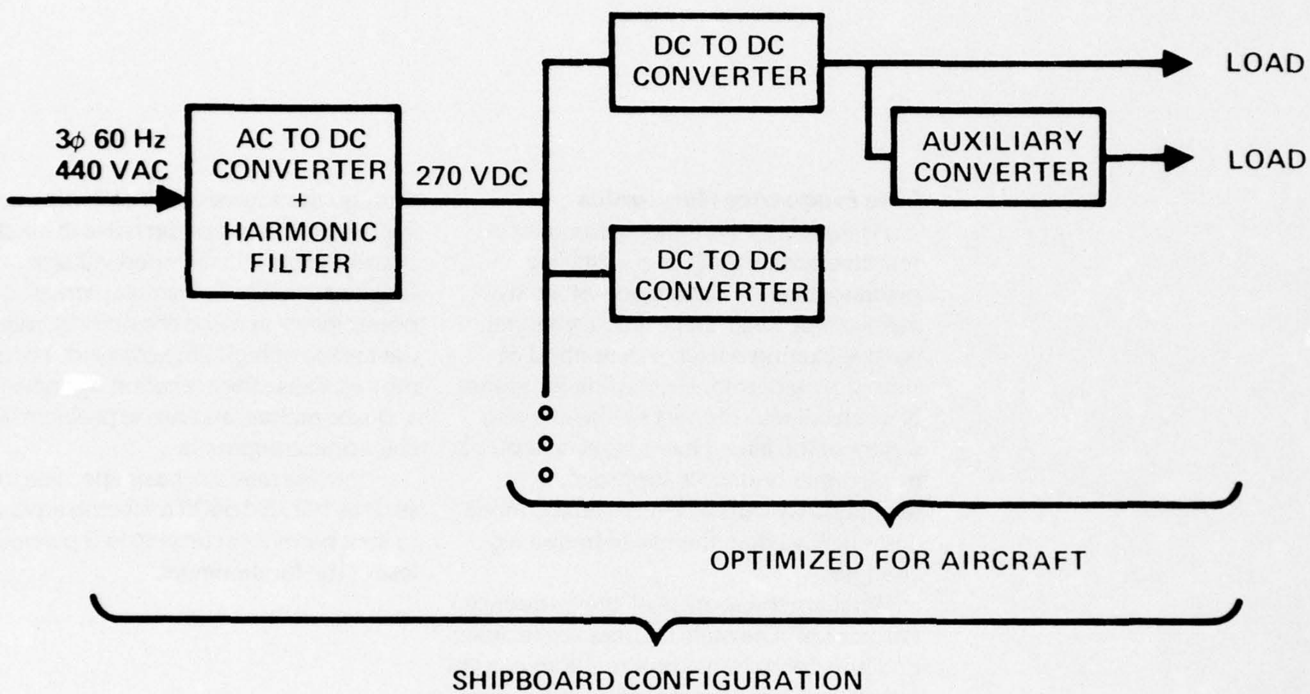
- Require electronic equipment to
  - Eliminate fans and blowers
  - Use frequency independent fans or blowers
  - Use platform prime power to drive fans or blowers

## *Standard Electronic Module Program*

The Navy Standard Electronic Module (SEM) R&D program is aimed at developing a standard family of power supplies that can be used with SEM and other modules in aircraft and shipboard applications. Because of the size and weight restrictions on aircraft, the aircraft requirements have predominated in the configuration selection. As presently conceived (starting FY 77), the basic power supply is a switching regulator dc-to-dc converter that accepts either 3 $\phi$ 400-Hz 115/200 Vac power or 270 Vdc power, as defined by MIL-STD-704B. (270 Vdc is obtained when 115/200 Vac power is rectified.) Output voltages are pin-programmable 5/5.2 Vdc, 12/15 Vdc, or 25/28 Vdc in various power ranges from 50 to 360 W. Since +5 V is required in most systems, small auxiliary converters (5 W, 15 W, 25 W) are available to provide $\pm5$, $\pm15$, and $\pm25$ Vdc from a 5 V source provided by a basic converter.

The basic dc-to-dc converter is not compatible with shipboard power sources either in harmonic currents drawn or in voltage level. Therefore, a shipboard converter is added that accepts 3 $\phi$ 60-Hz shipboard power and converts it to the 270 Vdc accepted by the basic converter. The shipboard converter also contains the harmonic filters necessary to attenuate rectification harmonics to acceptable levels. The shipboard converter consists of a transformer-rectified set and the harmonic current filter. Only one shipboard converter is required per cabinet or subsystem. None of the present approaches to reducing harmonic currents is considered fully satisfactory. Keeping the harmonic filters as separate units allows improvements in filter technology to be incorporated into systems with no impact on the basic power supplies or the rest of the system. Harmonic current reduction is an important technical consideration in shipboard electronic equipment design and is discussed further.

## Standard Electronic Module Program R&D Power Supply



***Line Frequency Harmonics***

As noted before, the only frequency-sensitive components in a switching regulator power-conversion system are passive harmonic filters. If conventional passive filtering is used as a method of suppressing harmonics, the line frequency has considerable impact on the size and weight of the filter. However, even a 60-Hz transformer harmonic suppression technique (discussed later) is much more cost effective than the use of frequency changers.

What are the sources of line-frequency harmonics? The main sources are rectifiers and iron-cored transformers. Other current harmonics, sometimes termed "abnormal," can arise from phase unbalances in the supply voltages, asymmetrical firing angles of controlled thyristors, and harmonic voltages in the powerline.

Harmonic currents in a shipboard power system can distort the voltage waveform through the source and distribution system impedances and can decrease the system's power factor. *The distorted voltage* waveform in turn can cause increased power losses in magnetic devices, reduce the torque of high-efficiency induction motors, cause the excitation of undesirable acoustic modes, and cause problems in electronic equipment.

For these reasons, basic specifications such as MIL-E-16400 are being amended to limit harmonic currents to 3 percent or less of the fundamental.

## Line Frequency Harmonics

- Generated by power supplies
  - Rectifiers
  - Iron-cored transformers
  - Abnormal harmonics

    Phase unbalances

    Asymmetrical thyristor firing angles

- Problems if excessive harmonics
  - Power losses in magnetic devices
  - Torque reduction in induction motors
  - Excitation of undesirable acoustic modes
  - Electronic equipment problems

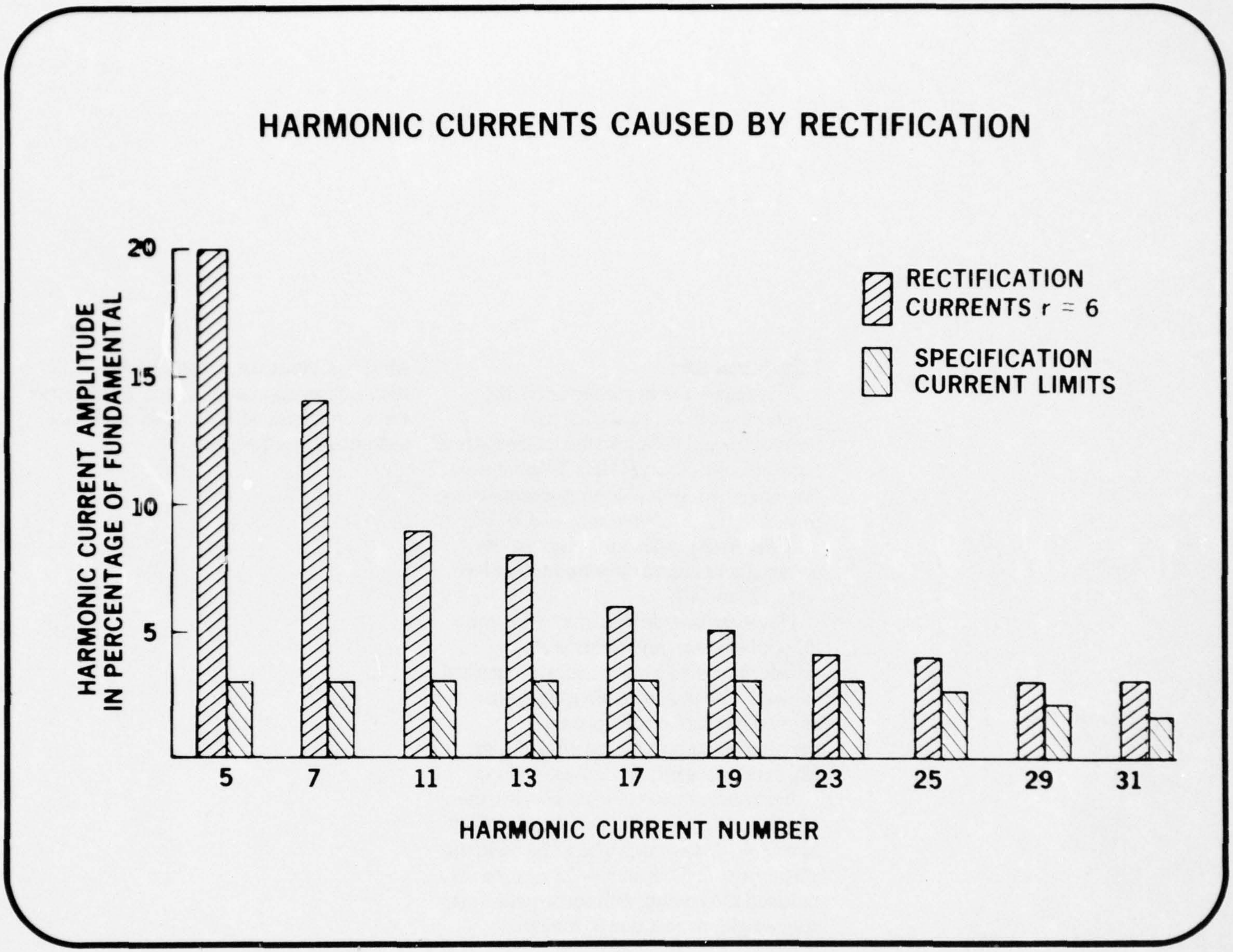
- New tighter current specifications
  - 3% or less of fundamental

### *Rectification Harmonics*

Rectification is the primary source of harmonic currents. The maximum harmonic content is related to the ripple factor, which is the number of ripple cycles per fundamental period in the output dc waveform of the rectifier. The harmonic content is independent of the transformer or diode interconnections used.

The case in which $r = 6$ is of interest because it represents the full-wave three-phase bridge rectification configuration currently in wide use in military electronic systems and, significantly, in the new power supply technology. This configuration is used almost exclusively in modern switching regulator power electronics because of its suitability for three-phase direct rectification (with no intermediate transformer) in the conversion to dc power.

The 3 percent specification limit is much tighter than can be met by the $r = 6$ case, the lower harmonics (5, 7, 11, 13) requiring large filters for their attenuation. A potential solution is to go to a higher ripple factor, which will result in a lower harmonic content.


HARMONIC CURRENTS CAUSED BY RECTIFICATION
HARMONIC CURRENT AMPLITUDE IN PERCENTAGE OF FUNDAMENTAL
20
15
10
5
RECTIFICATION CURRENTS r = 6
SPECIFICATION CURRENT LIMITS
5
7
11
13
17
19
23
25
29
31
HARMONIC CURRENT NUMBER

### *Ripple Factors*

The higher the ripple factor (r), the greater the cancellation of certain harmonics and therefore the lower the total harmonic distortion (THD). Theoretically, only $rm \pm 1$ harmonics are present, where $m = 1, 2, 3, \ldots$. Values of $r = 3, 6, 12,$ and 24 are of practical significance. As shown, there are no even harmonics for $r = 6, 12,$ and 24.

However, in order to use $r = 12$ or $r = 24$ ripple factors, an intermediate transformer is no longer optional but must be used. The higher ripple factors are created by more windings on the transformer or by multiple transformers, which produce required phase shifting.

If a transformer is already present, the 31 percent total harmonic distortion (THD) of an $r = 6$ system can be reduced to the 15 percent THD of an $r = 12$ system, at a reduced kVA rating, with some penalty in size, weight, or cost due to multiple windings. However, in the direct rectification approach, using a transformer for this purpose adds a considerable size, weight, and cost penalty.

## HARMONIC CURRENTS($I_N$) CAUSED BY RECTIFICATION AS A RATIO OF FUNDAMENTAL CURRENT ($I_1$) FOR VARIOUS SECONDARY RIPPLE (r) FACTORS

| HARMONIC | $I_N/I_1$ | | | | |
|---|---|---|---|---|---|
| | r | | | | |
| N | 3 | 6 | 12 | 24 | SPECIFICATION LIMIT* |
| 2 | 0.50 | – | – | – | 0.03 |
| 4 | 0.25 | – | – | – | 0.03 |
| 5 | 0.20 | 0.20 | – | – | 0.03 |
| 7 | 0.14 | 0.14 | – | – | 0.03 |
| 8 | 0.13 | – | – | – | 0.03 |
| 10 | 0.10 | – | – | – | 0.03 |
| 11 | 0.09 | 0.09 | 0.09 | – | 0.03 |
| 13 | 0.08 | 0.08 | 0.08 | – | 0.03 |
| 14 | 0.07 | – | – | – | 0.03 |
| 16 | 0.06 | – | – | – | 0.03 |
| 17 | 0.06 | 0.06 | – | – | 0.03 |
| 19 | 0.05 | 0.05 | – | – | 0.03 |
| 20 | 0.05 | – | – | – | 0.03 |
| 22 | 0.05 | – | – | – | 0.03 |
| 23 | 0.04 | 0.04 | 0.04 | 0.04 | 0.03 |
| 25 | 0.04 | 0.04 | 0.04 | 0.04 | 0.027 |
| 26 | 0.04 | – | – | – | 0.025 |
| 28 | 0.04 | – | – | – | 0.022 |
| 29 | 0.03 | 0.03 | – | – | 0.020 |
| 31 | 0.03 | 0.03 | – | – | 0.018 |
| THD | 0.68 | 0.31 | 0.15 | 0.08 | |

* MIL - E - 16400G AMENDMENT 1

### *Harmonic Suppression*

The principal methods of diminishing the harmonic output of converters have been

a. To increase the pulse number.

b. To install filters.

Newer techniques which show practical promise for the future have been discussed in the literature. These include novel active filters (harmonic injection techniques), multilegged reactors (or transformers), system cancellation techniques, and reduction of abnormal harmonics. However, most of the newer possibilities rely on the use of a transformer.

There seems to be a concensus that if the pulse number is increased from the usual 6, it should not go above 12. Most references state that the reason for this is simply economic. Others, however, make the following more specific claims. The multiplicity and asymmetry of the windings in many 12-pulse and in most above-12-pulse transformers lead to instability; and expensive, low-utility systems are required to restore stable operation. Multiple and asymmetric windings also produce abnormal (or uncharacteristic) harmonics on the ac line. Depending on the system, the low uncharacteristic orders may have about the same magnitudes as the characteristic harmonics. Magnitudes of uncharacteristic harmonics were found in field tests: 2nd, 5th, 8th, 9th, and 12th harmonics were greater than the 13th for a 12-pulse operation.

Passive filters, even for a 400 Hz, are prohibitively bulky and heavy if considerable low-frequency harmonic suppression is required. The problem of impedance mismatching can cause wide discrepancies in filtering parameters. Also, there may be system disadvantages in the use of passive filters, since the shunt-connected filter represents a low-impedance point for ambient harmonics in the power system.

Active filters using solid-state devices can considerably reduce size and weight, though not necessarily cost and complexity. Care must be exercised to avoid positive feedback paths which would cause instability.

The newer techniques have not yet been put into practice, but they do show promise. The harmonic injection technique is appealing; all existing harmonics can be reduced by injecting a third harmonic. Cancellation can also be achieved through the use of properly phased multilegged reactors. It would appear that the future holds promise for effective harmonic suppression, provided sufficient effort is expended.

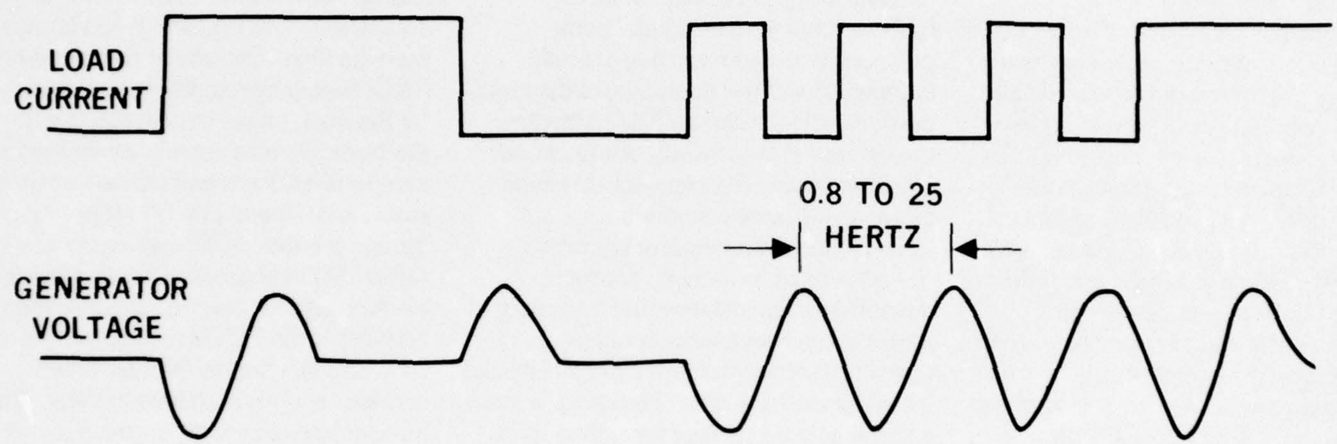
# Harmonic Suppression

- Increase pulse number (phases)
- Passive filters
- Active filters
- Novel active filters (harmonic injection)
- Multi-legged reactors
- System cancellation techniques
- Reduction of abnormal harmonics

### *Pulse Power*

The way the electrical power system responds to pulse loads can be another *technological problem. Pulse loads are* caused by a variety of conditions, including weighing anchor and the pulsing of radars and sonars. The electrical generator response to a single step change in load is similar to the familiar response of a well-damped second-order control system. This single response may or may not be a system problem. If the step load is repeated at frequencies related to the characteristic response of the generator, usually between 0.8 and 25 Hz, a modulation of substantial amplitude can occur (80 V peak-to-peak on Type I 440 Vac power). A standard solution to problems of this type has been to specify 400-Hz power and use a motor-generator set as a filter between the ship's 60-Hz system and the pulsing load. The inertia of the MG set is thus utilized to provide the filtering action. MG sets are neither designed nor specified for this filtering application—but they do work. The efficacy of the new solid-state frequency changers as pulse filters has not been shown. In any event, the solution is costly in size, weight, reliability, and dollars, and better solutions are needed.

# GENERATOR RESPONSE TO LOAD CHANGES



***Technology Summary***

This study has shown that the practice of designing electronic equipment to use 400-Hz power input for the purpose of saving weight and size in the electronics is costly when such equipment is specified for ships with 60-Hz prime electrical power. The added weight and size of the frequency changers that must be installed to provide the 400-Hz input negate the minor effect of any weight savings in the electronics. Furthermore, the added complexity creates other problems. The same would be true if 60-Hz equipment power were required on ships such as the PHM-1, which have 400-Hz prime electrical power. Technology exists that allows frequency independent electronic equipment to be designed that will accept either 60-Hz, 400-Hz, or dc input power. The switching regulator power-conversion circuitry in this new technology is lighter and smaller than conventional 400-Hz power-conversion circuitry. It should be kept in mind, however, that to develop electronic equipment and systems that are fully independent of the frequency of the input power would require an R&D program concentrating on a variety of associated electromagnetic devices — motors, fans, blowers, and circuit breakers.

Frequency independent electronic systems would have many potential advantages. For instance, the frequency of a platform power source could be optimized without regard to the electronics. If 400 Hz or some other frequency is more suitable as prime power for certain high-performance ships, a change of power frequency could be made without redesigning the electronics.

As desirable as frequency independent power would be in the long run, the immediate problem is the wastefulness of using 400-Hz power on 60-Hz ships, a system which requires that a frequency changer be installed ahead of the 400-Hz equipment. This problem is less complex than the long-term one and requires little R&D. Switching regulators now being used for the main power conversion in new electronic designs are inherently frequency independent. Fans and blowers are now required to operate on 60-Hz power, even though the associated electronics may require 400-Hz power. Other required electromagnetic components either have both 60-Hz and 400-Hz versions that are form and fit interchangeable (circuit breakers and running time meters) or use an alternate technical approach to the function (servo mechanisms). Two problems still exist that require R&D for 60-Hz, 400-Hz, and frequency independent systems. These are

a. How to best suppress or compensate for harmonic currents.

b. How to prevent pulse loads from interfering with other equipment.

## TECHNOLOGY SUMMARY

### TECHNOLOGY/APPROACHES AVAILABLE TO ELIMINATE FREQUENCY CHANGERS

- SWITCHING REGULATORS
  - INHERENTLY FREQUENCY INDEPENDENT
  - SMALLER, LIGHTER, MORE EFFICIENT
  - AVAILABLE AND IN USE
- MOTORS, FANS, BLOWERS
  - SELECT TO OPERATE FROM PRIME POWER SOURCE
  - FREQUENCY-INDEPENDENT DESIGN FEASIBLE
    - MORE COSTLY AND R&D REQUIRED
- OTHER ELECTROMAGNETIC COMPONENTS
  - 60 Hz/400 Hz COMPATIBILITY AVAILABLE
  - ALTERNATE TECHNOLOGY AVAILABLE
  - FREQUENCY-INDEPENDENT DESIGNS FEASIBLE WITH R&D
- HARMONIC CURRENT SUPPRESSION AND PULSE LOADS
  - A PROBLEM FOR 60-Hz AND 400-Hz POWER
  - BETTER SOLUTIONS REQUIRED

## Conclusions

Frequency changers and a dual distribution system are required on a ship if equipment is installed that uses an input *power frequency different from that of the* ship's prime electrical source. The major problem is providing 400-Hz requirements on 60-Hz ships. Most ships have 60-Hz prime power but carry much 400-Hz *equipment*. The practice of providing 60-Hz power on the few high-performance ships with 400-Hz prime power sources is equally troublesome. Frequency changers, required in either case, have high *acquisition costs, operating costs, and* system penalties. Switching regulator technology is inherently insensitive to the frequency of the input power, and is being increasingly used on ships because it has advantages *in size, weight, and efficiency.*

Properly applied, switching regulator technology reduces the need for frequency changers on ships, with substantial cost savings and system benefits. The required changes can be implemented mostly through education, policy statements, and specification changes; little R&D is directly *needed. On the other hand, electronic* equipment that is fully independent of powerline frequency is now technologically feasible, but would require extensive R&D programs to develop qualfied frequency-independent electromechanical parts.

There are two technical problems concerning the power interface that do require R&D efforts to find better solutions than those now available. First, how best to *reduce or compensate for harmonic* currents in power lines caused by rectification and other electronic equipment nonlinearities. Second, how to suppress or compensate for pulse loads so that they don't degrade the power system.

## CONCLUSIONS

- USE OF POWER FREQUENCIES DIFFERENT FROM THE PLATFORM PRIME POWER REQUIRES FREQUENCY CHANGERS
- FREQUENCY CHANGERS HAVE HIGH ACQUISITION, OPERATING AND SYSTEM COSTS
- TECHNOLOGY IS AVAILABLE THAT ELIMINATES THE NEED FOR FREQUENCY CHANGERS
- THE TECHNOLOGY IS BEING USED IN SHIPBOARD ELECTRONICS FOR OTHER REASONS
- PROPER APPLICATION OF THE TECHNOLOGY WILL REDUCE THE REQUIREMENT FOR FREQUENCY CHANGERS
- SUBSTANTIAL COST SAVINGS AND SYSTEM IMPROVEMENTS WILL RESULT
- REQUIRED CHANGES CAN BE IMPLEMENTED THROUGH EDUCATION, POLICY STATEMENTS, AND SPECIFICATION CHANGES WITH MINIMUM R&D
- WHETHER IMPLEMENTED OR NOT TWO TECHNICAL PROBLEMS REMAIN
    - REDUCTION OF HARMONIC CURRENTS
    - POWERING PULSE LOADS

## Recommendations

This study concludes that the need for frequency changers can be reduced over a period of years primarily by the processes of education, policy statements, and specification changes. Some technical support to SYSCOMS and contractors will be necessary.

This report is part of the education process necessary to accomplish the change. If the reader is convinced of the validity of the key ideas in this report, he is invited to help in this education process by making the ideas known to others. If the reader is not convinced, he is invited to continue the discussion with the authors or sponsors. Any hidden problems need to be surfaced and resolved to make the process work. Extensive briefings are also recommended.

A NAVMAT policy statement to procure equipment compatible with the platform primary power source would give authority and direction to necessary specification and standard changes and would tighten the control on waivers and deviations. Such a policy statement, in NAVMAT INST format, is recommended.

There is nothing now in the specifications and standards that prevents the designing of electronic equipment that is frequency compatible with the platform prime power source. However, merely a lack of constraint is not sufficient to bring about compatibility. Modification of the specifications, primarily MIL-STD-1399, Sec 103, and MIL-E-16400, is recommended to strengthen them in this area.

While many Navy programs and equipment, such as AEGIS, TRIDENT, AN/UYK-20, and AN/SPG-51, use the switching regulator technology described, they use it with mixed degrees of success. Some acquisition managers and contractors are relatively unfamiliar with the technology. The technical expertise needed by program managers, acquisition managers, and contractors is present in the Navy laboratory structure and in some Navy field activities. It is recommended that this support be made available.

Finally, this study reviewed the technology available to suppress or compensate for harmonic currents and pulse currents in the power distribution system. There are solutions, but this study found none of them fully satisfactory. Various low-level R&D activities are engaged in the search for better solutions, but an expanded effort seems necessary if problems associated with harmonics and pulse currents are to be dealt with in time to support the need.

# RECOMMENDATIONS

- EDUCATE THE NAVY TECHNICAL AND MANAGEMENT COMMUNITY ON THE COST OF FREQUENCY CHANGERS AND THE OPPORTUNITY TO REDUCE THE NEED FOR THEM
- ESTABLISH A POLICY TO USE POWER AS GENERATED BY THE PLATFORM PRIMARY ELECTRICAL POWER SOURCES
- MODIFY SPECIFICATIONS AND STANDARDS TO IMPLEMENT POLICY
- PROVIDE TECHNICAL SUPPORT TO ACQUISITION MANAGERS AND CONTRACTORS UNFAMILIAR WITH THE REQUIRED TECHNOLOGY AND DESIGN APPROACHES
- EXPAND R&D ACTIVITIES ASSOCIATED WITH HARMONIC CURRENT SUPPRESSION AND PULSE LOADS