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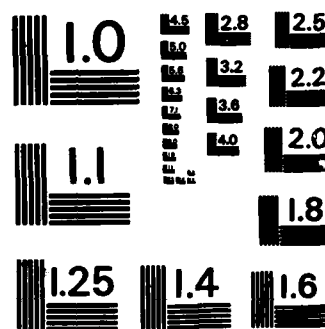
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NAVAL AIR ENGINEERING CENTER

REPORT NAEC-92-170

60-HZ TO 400-HZ
ELECTRICAL POWER
CONVERSION

Advanced Technology Office
Support Equipment Engineering Department
Naval Air Engineering Center
Lakehurst, New Jersey 08733

8 November 1982

Final Report
AIRTASK A03V3400/051B/1F41461000 WU 203

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Prepared for
Commander, Naval Air Systems Command
AIR-340E
Washington, DC 20361

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60-HZ TO 400-HZ
ELECTRICAL POWER
CONVERSION

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER NAEC-92-170	2. GOVT ACCESSION NO. AD-A222 040	3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) 60-HZ TO 400-HZ ELECTRICAL POWER CONVERSION		5. TYPE OF REPORT & PERIOD COVERED Final	
7. AUTHOR(s) Francis V. Kern		6. PERFORMING ORG. REPORT NUMBER NAEC-92-170	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Air Engineering Center Support Equipment Engineering Department (92A3) Lakehurst, NJ 08733		8. CONTRACT OR GRANT NUMBER(s)	
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command AIR-340E Washington, DC 20361		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AIRTASK A03V3400/051B/1F41461000	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE 8 November 1982	
		13. NUMBER OF PAGES 25	
		15. SECURITY CLASS. (of this report) Unclassified	
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited			
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)			
18. SUPPLEMENTARY NOTES			
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) ELECTRICAL POWER ELECTRICAL POWER CONVERSION 400-HZ POWER DISTRIBUTION 400-HZ MOTOR GENERATORS SOLID-STATE GENERATION			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Report comments on present 400-Hz power distribution methods, presents a study to determine optimum 400-Hz power sources, and recommends a possible future source.			

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SUMMARY

A. ADVANTAGES. 400-Hz power is extensively used in avionics, shipboard applications, and maintenance facilities. There are advantages in the use of a 400-Hz power line:

1. In transformer rectifier conversion to DC power applications, filtering can be accomplished with much smaller and more inexpensive components, because the "ripple frequency" is increased by a factor of over six times.
2. The aircraft industry selected 400 Hz many years ago for their work because of the fact that equivalent powers can be achieved with substantial weight and size savings over "standard" 60 Hz.
3. Now we have "off-the-shelf" equipment at a competitive price. When considering an entire system installation, this can mean an overall lower cost.
4. 400-Hz power systems can respond up to 6 times faster than 60 Hz. Position accuracy of linear differential transformers and servo torque motors are also much better at 400 Hz.
5. Torque is higher and acceleration faster.
6. There is less electrical noise in the area compared to 60 Hz.
7. A 400-Hz system is not an even multiple of 60, and therefore free of 60-Hz line variations.
8. Inventory control is a little easier, because parts which cannot be used on utility power are not likely to be taken for use in another area.

B. DISTRIBUTION. 400-Hz power hasn't been really exploited until now because of the difficulty in achieving precise control of it, in a 60-cycle world. Traditionally, 400-Hz power for industrial use has been obtained from a very large, 60-Hz to 400-Hz heavy motor/generator set located in an equipment room at the facility. A handling problem is apparent in even the smallest size. Because of the economics involved, synchronous sets are usually installed in sizes of 25 kva and up. The 400-Hz power is then bussed around the facility. This introduces new problems, even after special design considerations have provided for the radiated effects of 400-Hz power, when it is transmitted over a distance of several hundred feet. One problem is that because a central 400-Hz supply is used, it must be in operation any time a single machine needs power. Thus the 400-Hz generator is running all the time, possibly to supply just 1 or 2 kva to one test bench. This is very expensive power, possibly as much as several dollars per kwh. A second problem is voltage regulation. When the bus is used by several people simultaneously, the voltage fluctuates on the bus whenever one of the power users changes conditions. This could upset the other users, particularly if they require sensitive control. Finally, the larger systems are relatively expensive to maintain.

C. MOTOR GENERATOR. 400-Hz power generation at the present time would be most economically accomplished by multiple, low power, low-cost, speed-controlled, 60-Hz AC induction motor/400-Hz AC generator sets.

D. SOLID-STATE GENERATION. 400-Hz power generation in the near future will be accomplished by waveform synthesis, using solid-state switching techniques. Microcomputer control of the inverter equipment will aid in improving the control and output quality of the power delivered. The necessary technology exists at present. Some of the required hardware is being developed and refined now, particularly high-power, high-voltage transistors. There are a few commercial concerns which now produce 400-Hz solid-state supplies. Most present supplies do not meet the military specifications, set for mature 60-Hz supplies, for electromagnetic interference, harmonic content, and efficiency. There are large size and weight advantages to be gained by the use of some types of solid-state 400-Hz power sources. Many existing supplies suffer from an attempt to get line triggered, self-commutating, low-cost, minimum part count, silicon controlled rectifier (SCR) controlled designs. The most popular is called a "6-step" inverter which is a very crude sine wave approximation. Some "DC link" designs remove the need for line synchronization. Most DC link systems employ rectification, voltage magnitude control, and an inverter. In circuit design, it may be profitable to keep these efforts separate. Three-phase, six-diode rectification, pulse-width modulation for DC voltage control, microcomputer controlled parallel inverters, with 400-Hz, 4-wire isolated output transformer pulse addition holds promise for improvement.

E. RECOMMENDATIONS. The research and development (R&D) effort should be continued in this area. Military R&D 6.2 prototype development activity such as the Army's 15-kva mobile unit should be sponsored. Study should also continue to monitor solid-state frequency converter developments as a suitable unit should be available in the future. Commercial products such as Topaz's 3-kva resonant unit should be sampled.

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I. INTRODUCTION

A. BACKGROUND

1. PROBLEM. Numerous requirements exist today for 400-Hz power in areas where only 60-Hz power is available, and these requirements are expected to increase in the future. The MMG-1A/-2 and MG-1/-2 motor generator sets and solid-state frequency converters are presently unsatisfactorily fulfilling these requirements. These systems have problems meeting the quality of power required by the latest revision of MIL-STD-704. In addition, poor efficiency ratings and reliability have been a problem with some equipment.

2. TASK. The Naval Air Engineering Center (NAVAIRENGCEN) has been tasked by the Naval Air Systems Command (NAVAIRSYSCOM) to conduct a study to determine the optimum technique for generating quality 400-Hz power from 60-Hz power. This report will attempt to commit to paper the many facets of thought that have evolved from the study so far. It is evident that some form of stationary, solid-state inverter will be the best method of converting available 60-Hz power to 400-Hz power in the future. It is not as apparent, however, as to what direction NAVAIRENGCEN efforts should be directed at the present time, in supplying support equipment to fill the need for testing Navy 400-Hz electrical equipment.

B. PLANNING

1. An abundance of new and sometimes complex technology is coming on the scene and it is accompanied by high hopes for drastically improving or replacing existing products. As much as we would like to receive the benefits of such technology at once, we have to ease it in at the rate at which we can check it and test it, and assure ourselves that we won't be in charge of its recall sometime in the future. When it comes to the selection and application of new technology, the one who stakes his or her reputation on the outcome should be entitled to first choice--that is the job of the design engineer. The hunt does not have to be limited to the designer on the job; the entire engineering staff, management, research and development staff including consultants, all can be looking for better solutions to support equipment problems. Design engineers become frustrated when management hands them new developments to use. The logical order of progress is for the design engineer to define the limiting factors in a product or system and hunt through new technology for ways in which to overcome these roadblocks. This has been partially accomplished by revision D to MIL-STD-704. Long-term planning is needed to make sure new technology and high technology get the time to be planned properly into equipment development. The danger is that a miscalculation can set back technology incorporation.

2. The NAVAIRENGCEN has already conducted some premature testing of solid-state inverters with negative results. Solid-state inverters still have problems with efficiency, harmonic distortion, line isolation, parallel operation, and misdirected goals. Nevertheless, due to the lack of rotating parts, much less weight, better size-to-horsepower ratios, future cost savings, and other less obvious advantages, this type of conversion offers the best future alternative to date for frequency conversion of power sources. There is some very good research and development (R&D) work being carried on in power switching. One of

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the primary motivating forces for this work is the effort to obtain AC motor control by adjustable frequency power generation. A huge commercial market exists for a truly efficient, reliable, low-cost product. Frequency power conversion for other purposes is akin to this effort. There are several low-power, 3-kva, commercial solid-state inverter, 400-Hz sources available but not to military specifications. A ruggedized 15-kva R&D prototype unit was developed for the Army by Delco in 1980; the unit weighed approximately 200 pounds, was approximately 12 cubic feet in volume, and 73% efficient at full load, worse at low loads. Bendix is doing some interesting work on aircraft 400-Hz supplies using DC line-driven inverters. The advent of a 400-Hz unit suitable for field deployment is fast approaching.

II. POWER DISTRIBUTION

A. POWER SURVEY

1. A survey of Marine Corps support van power was made in 1978 by the NAVAIRENGCEN Test Department, and the results reported in NAVAIRENGCEN report TPR 78-12. Upon reviewing this report, several conclusions were reached. The vans (Mobile Facilities (MF)) are arranged into an Integrated Mobile Facility Complex. The largest complex had 93 vans, the smallest had 25 vans. The 60-Hz power distribution installation in most cases is good. Power is subdivided into smaller distributions with separate power disconnects and breaker protection. The report, TPR 78-12, is recommended reading for the activities surveyed.

2. SURVEY DISCUSSION. These installations seem to suffer from three common faults:

- a. The belief that if a little consolidation is good, then more must be better.
- b. They are overly influenced by a natural trend to over-specify/over-design to cover possible future needs.
- c. The social tendency to form in groups for mutual support in some cases seems to be overdone.

The generators in almost all cases are much larger than required. The circuit breakers are often rated too large to be protective. A small power user must suffer from the deterioration of power quality caused by a large power user. All those factors seem to be even more apparent in 400-Hz distribution. In some cases grouping of users reached the point where the large increase in reliability due to the availability of two supplies was lost, maintenance time became lost downtime. An effort should be made to avoid the constant march toward more power and heavier equipment unless fully justified.

B. LARGE POWER UNIT

1. While grouping several light-demand vans to a common redundant source appears to have merit, coupling these many users in a common network with a few high-power users can be disastrous. Frequently the high-power users are pulse power users such as beacons or radar. Phase power unbalance and line drop problems can be easily corrected among many light-demand users by redistribution of load. A phase or line drop unbalance by a single large power user is sometimes very difficult to cure. Therefore, it would appear better to remove the few large power users from the distribution grid and supply power to them through a separate isolated or parallel feed.

2. Given the energy considerations present today, it is questionable whether we can continue to use diesel motor generators in fixed base installations for continuous 60-Hz power generation. While such generators afford mobility and may be economical for intermittent large power demands where downtimes are much larger than demand times. The basic inefficiency of the diesel

engine is approximately 30% times the 85% efficiency of the generator for a resultant 25%. This is a large price to pay where these advantages are not needed. Increased consideration of the use of public utility or base power should be considered, with some form of mobile inventory item backup power generation available. 400-Hz power can be more economically and reliably supplied by an inexpensive 60-Hz AC motor, speed controlled by slip, coupled to a 400-Hz AC generator. The efficiency would be approximately 80%. Electric machines have efficiencies which are quite high compared to steam, gas, or oil driven units. Therefore, the diesel motor/AC generator system perhaps should be considered only as a backup for fixed installations and overseas deployment.

C. NETWORK DESIGN. Reasonable design of layout and wiring is required even in the distribution of 60-cycle power to many small users, to save the repeated cost of equipment. Reliability improvement can be obtained by judicious design. It may be better to set up several independent distribution networks matching the number of smaller equal power sources, than to have one network with one or two larger power sources. If the independent networks can be interconnected or isolated at a central location, several advantages ensue. Under light load conditions, the networks can be paralleled and run from one unit, the others being shut down. This would extend the life of the non-operating units, conserve their standby power, and allow more efficient operation of the operating unit. When the load increases, a second unit would come on and the network would become two independent networks. This would reduce the interaction of loads and the need for parallel operation of power sources. This is always a tricky phase matching, load sharing operation. As the load further increases, a third unit would come on causing a subdivision of networks into three. This process would continue until all power sources were on, supplying their individual networks. Under lessening loads, the reverse would occur. Since it is unlikely all would fail at once or be needed at one time, the maintenance window would be enlarged. All power source units could be the same, leading to greater common support equipment with resultant savings in required inventory and required logistics support. This scheme could be automated by sensing the load. If the power interconnection panel is centralized, reduced wire length and voltage drop would result. Since heavy load conditions would not result in additive currents over a common run, smaller distribution wire could be used. The design could be standardized and modularized to become NAVAIRENGCEN supplied support equipment. The distribution would then be under design control where it could be improved and updated.

D. WIRE CABLE. The interconnecting wire itself should be improved, upgrading the insulation to a higher class such as a fluorinated ethylene propylene. This would reduce a four-wire cable's outer diameter for the same current carrying ability and allow a greater short-time overload. The wiring should be raised above ground traffic and moisture for safety, perhaps, on poles at the corners of the vans.

E. 400-HZ DISTRIBUTION. The concept of a distribution network of 400 Hz in itself is a questionable policy. In essence, for AC motor/AC generator sources power already distributed as 60 cycles is being redistributed as 400 cycles. It would appear better to convert the 60 Hz to 400 Hz at the point of need. With the advent of solid-state conversion units, this approach is much more attractive. The units could then be configured to the type and amount of

power required. The Marine vans survey report, NAVAIRENGCEN Test Department TPR No. 78-12, mentions that only 15% of the 400-cycle power need be TYPE III of MIL-STD-1399, the remainder can be utility power TYPE II. Conflicting military specifications are being quoted for the required power quality: Shipboard, 3 types, MIL-STD-1399/300G; aircraft, MIL-STD-704D; and mobile, MIL-STD-1332. The largest single load at present appears to be 30 kva. The power which requires tight specifications in general are the lighter loads. A utility-type power requirement, say TYPE II of MIL-STD-1399, could be further regulated by line regulators and transient snubbers at the point of need, to meet MIL-STD-704D specifications, removing the need for stricter specifications for the larger utility power source. The modular power unit should not be much larger than the largest single-power user's demand or approximately 30 kva. The unit could be smaller if modular units are run in parallel to supply this user.

III. POWER SOURCES

A. 400-HZ SOURCES. A power source that may be the best under one consideration such as cost may not coincidentally be the best in terms of technical performance, size, weight, future technology trends, reliability, flexibility, commonality, or other considerations. Some of the possible sources of 400-Hz power are:

- Diesel motor/AC generator
- AC motor/AC generator
- Solid-state rectifier/inverter
- DC motor/AC generator
- Roesel generator (an innovative rotary design)
- AC motor/DC motor/AC generator (Ward Leonard system)
- Permanent magnet DC motor/AC generator
- Frequency synthesizers
- Driven aircraft generators
- Other commercial and military inventory items

B. AC MOTOR/AC GENERATOR SETS. These units are combined in two basic configurations: a synchronous motor driving an AC generator and an induction motor driving an AC generator.

1. SYNCHRONOUS MOTOR/AC GENERATOR. In the past, 400-cycle power generators were almost universally associated with rotating machinery for converting power from 60-cycle power lines. For larger installations synchronous AC motors driving synchronous AC generators have been used for 400-Hz generators. These units are very stable in frequency but also very expensive. They require no speed control since speed control is inherent in a synchronous machine. The most common combination is an expensive one: a 1200-rpm, 6-pole, 60-Hz motor driving a 40-pole, 400-Hz generator. A 40-pole machine is expensive. If the utility frequency changes to 50 Hz, common in Europe and some sections of western United States, the equipment could become obsolete.

2. INDUCTION MOTOR/AC GENERATOR. It is difficult to find a more efficient and reliable, low-cost combination than a 60-Hz AC induction motor driving a 400-Hz AC generator. At significant loads the efficiency of the AC induction motor approaches 90%. The generator is similar. The overall efficiency is about 80%. The weight is enormous since the machine is almost solidly packed with iron and copper. A 40-hp (30-kva) generator set would weigh about twice as much as a 40-hp motor, or approximately 3,000 pounds. By comparison, a 15-kva solid-state inverter unit (developed under a 1980 MERADCOM, Fort Belvoir, R&D contract for the U.S. Army by Delco) weighed approximately 185 pounds. Therefore, a 30-kva (40-hp) unit would weigh about 400 pounds. This is a considerable savings if the unit must be air transported or becomes shipboard equipment.

a. Induction Motor. The polyphase AC induction motor is the most common type of alternating-current machine. It is relatively cheap, rugged, and simple, and can be manufactured with particular characteristics to suit one's needs. It consists of two main parts: a rotor and a stator. The rotor may be wound in two ways: a squirrel-cage winding or a wound-rotor winding. Normally, the motor is a singly excited machine with the field winding receiving the

excitation potential. It may be installed in an austere environment and perform well despite the presence of moisture or dust in the atmosphere. Simplicity and ruggedness are two of its major assets. The stator, or stationary element in the motor, has wire coils wound around it for connection to the power supply. The rotor is a laminated structure with slots into which copper or aluminum bars are placed. The bars are all connected at the ends to a common conductive support ring.

b. Induction Motor Operation. When a polyphase alternating current is applied to the stator winding, a resultant magnetic field rotates around the stator at a speed dependent on the supply voltage's frequency. The stator is like the primary winding in a transformer, the squirrel-cage rotor acts as the secondary winding. A voltage is induced into the rotor bars and a current will flow in these bars. The current's magnitude is limited by the rotor's impedance. As the stator field turns, the rotor field will be compelled to follow it and start revolving. There is a maximum theoretical speed, called synchronous speed, where the rotor would rotate at the same speed as the stator field. This speed actually can never be attained because the rotor bars would not cut the stator field flux, no voltage would be induced, and no current would be generated. Since the rotor would not have current flowing in it, no torque could be developed. There must be a difference in speed between the rotor and the stator field. This is a phenomenon called slip. A finite amount of torque must be developed just to overcome friction core losses and windage in the rotor.

$$N_R = \frac{120f}{p} (1-S)$$

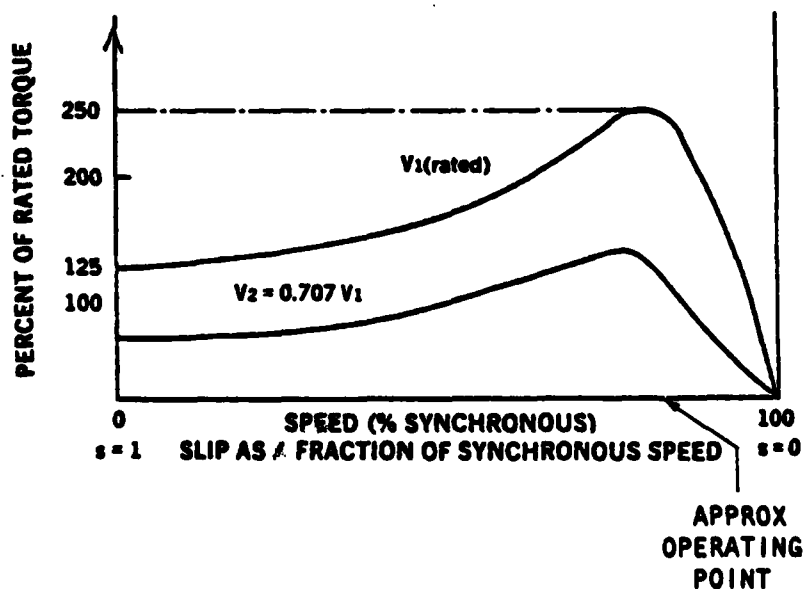
Where: N_R = rotor speed (rpm)

f = line frequency

p = number of poles

S = percent slip

Therefore, frequency, slip, and the number of poles are the variables controlling speed in an induction motor. The magnitude of the voltage applied to the stator affects the speed and torque of an induction motor. The following graph illustrates the effect of a change in voltage over the entire speed range. Slip speed control near synchronous can be obtained by line voltage reduction.



c. Induction Motor Generator (M/G) Speed Control. Since the speed control problem is one of maintaining a small deviation around a steady running speed, it can be controlled by controlling the slip of a high resistance rotor AC motor. The deficiencies of this type of control, small control range and poor efficiency if the speed reduction is large, would not be present in this application. However, some inefficiency will result. There will be about a 10% loss for a 20% speed reduction. The frequency of a generator is directly proportional to the number of machine poles and the speed at which it is driven.

$$f = (P/2) (N/60)$$

$$f = PN/120$$

where P = number of poles, N = rpm, and f = frequency.

The maximum synchronous speed of a 60-Hz, 2-pole motor is 3,600 rpm. To generate 400 Hz from a 16-pole generator, the speed must be:

$$N = \frac{(120) (400)}{16} = \frac{48,000}{16} = 3,000 \text{ rpm.}$$

Therefore, a 3,600-rpm motor must be slowed down by load and control to drive a 400-Hz generator. The speed reduction required is $\frac{600}{3,600} = 16.6\%$.

d. Torque. When the motor operates at reduced voltage, its reserve capacity for available torque is greatly reduced, especially if the speed is reduced more than 50%. Therefore, reducing the voltage has the disadvantage of reducing the available torque and motor efficiency for a given speed. However, if the speed reduction from synchronous is small, and the range of control is small, this method of slip control is effective.

e. Commutating Motors. Many systems for speed control use a DC motor. Though a relatively simple system when modern SCRs are employed, the motor's cost, size, and mechanical commutators present significant problems. Some methods of slip control for an AC motor also employ commutators, these again present maintenance and reliability problems. A simple reduction of line voltage on the stator winding would probably suffice for slip control. A tapped secondary winding of an isolation transformer to reduce voltage would result in little power loss. This voltage induction could also be accomplished by isolated solid-state relay switching or SCR pulse width modulation.

C. AIRCRAFT POWER. Another method of obtaining 400-Hz power for aircraft equipment test that would be very close to that of a customized motor/generator, would be a 3,600-rpm AC motor with a multi-roller fluid traction gear speed increaser of times 2 driving an inventory item, aircraft generator such as the M21480 integrated drive generator with its own internal regulation and frequency control.

D. ROESEL GENERATOR. This is an unusual form of an AC motor/generator where the generator writes its poles magnetically. Other innovative designs are cropping up in the power backup field. "PowerRotor" is the trade name for the Roesel generator. This variable-speed, constant frequency generator provides

continuous 400-Hz power whether the rotor frequency remains constant or varies. It provides 10 to 30 seconds of ride-through power during a brief outage, for an orderly shutdown. Like a giant tape recorder's write head, the unit is able to print poles on a spinning magnetic motor unit drum. By varying the poles, depending on rotational speed, the unit can maintain a constant rate. Although the rotational speed may be decreasing, the reprinted number of poles controlled by an independent source (which will be increased) will counteract this slowdown. Thus, the number of poles/second will remain constant. Furthermore, this unusual unit isolates a load from the utility power line, thus effectively isolating the load from line noise. If an orderly shutdown is required, this system is an alternative. While such schemes are worthy of consideration for specialized usage, I do not personally think we should commit to a single vendor and single specialized source for a requirement that is quite general. There will soon be several vendors of switching inverters when the systems quickly mature.

IV. SOLID-STATE RECTIFIER/INVERTER

A. STATE-OF-THE-ART. Recent solid-state switching device improvements have led to a resurgence of schemes which synthesize the desired waveform and frequency by discrete switching. There are many circuit configurations that will accomplish the same output waveform. Once triggered, an SCR biases itself into saturation. It is relatively easy to get into cross-conduction problems with SCRs because of these characteristics.

B. SILICON CONTROLLED RECTIFIERS. The most promising source of power for the 400-Hz need in the future is solid-state switching. This is a developing technology and has not reached full maturity for power distribution, although rapid strides are being made. One of the problems in utilizing this new technique is the insistence that the new power source meet the full specifications developed for the very mature 60-cycle power sources we now have. In particular, the requirement for parallel operation is difficult when SCRs are employed. The transient spikes that result from high-power, very short-time duration switching, though of low-energy content and relatively easy to filter, still exceed some EMI specifications established for other types of mature power sources. SCRs require very little power to turn on; therefore, their efficiency is high, but they can be more easily turned on inadvertently by transients. SCRs cannot be controlled for turn-off or biased-off easily. They must be back-voltaged or the current reduced to a very low value to be turned off. Until recently, transistors were not sized or packaged for large power control above 50 amps.

C. TRANSISTORS

1. Transistors can be biased off and require more power for turn-on; therefore, they can be more accurately controlled. There is a small increase in power loss with transistors at present, which may change with recent power transistor innovations. In applications where transistorized inverters are required, the designer is confronted with the task of selecting the proper semiconductor to achieve the output power inverter function. In the past, the power transistors available to the designer have consisted of power Darlington's rated to 50-amp continuous collector current, packaged in standard and modified TO-3 versions, rated to 20 amps and 50 amps respectively. Though this appears sufficient, it is necessary to parallel individual transistors for higher current ratings and to match switching times as well as transconductance of each transistor for higher horsepower. The matching is readily accomplished, though at increased costs to the user of the devices, but the device package has still presented a major problem.

2. In the TO-3 package, the collector is connected to the case. This necessitates that output transistors be isolated from each other and from the equipment enclosure, and that a concerted effort be made to conform to UL, NEMA, and other equipment standards for creepage and strike requirements. Clearly, a new approach to packaging power transistors would be desirable. A new package should meet NEMA and UL requirements for creepage and strike, should minimize or eliminate the need for paralleling devices at higher horsepowers, and eliminate the need for individual insulating. To meet these requirements, General Electric Company has recently developed a line of high-voltage, high-current, power Darlington transistors. Designated D66DV and D67DE, the transistors are rated

to 500V dc [$V_{CEO(SUS)}$] with continuous collector currents of 50 amps and 100 amps respectively. Both components have isolated, insulated collector packages, a feature particularly advantageous when using the devices where six or more devices per system must be utilized to implement the inverter function. Since the isolation voltage for the devices is greater than 2,500V rms, all devices can be mounted on a common heat sink.

D. SYSTEM WAVEFORMS

1. Currently almost everyone seems satisfied with a six-step inverter voltage waveform for frequency conversion. This approach which is aimed at the large commercial 60-Hz AC motor control market, is a minimum part count, low-cost, self-commutating design. Self-commutation, in this case, relies upon the incoming power frequency and load to establish the required triggers. The actual waveform applied to each phase is a current square wave in this system, and the harmonics associated with this waveshape are considerable. The harmonics of a triangular waveshape are less than a square wave. It may be worthwhile to attempt to improve this waveshape. If transistors or gated-off thyristors (GTOs) are used, the on and off times can be more adequately controlled than with SCRs. This control can be accomplished by discrete logic circuitry or microprocessor control. In a practical situation, it is necessary to provide some time delay between the positive-to-negative transition period in the phase current. This time delay enables the complementary transistor to turn off before its opposite member turns on, preventing cross conduction and eventual destruction of the power transistor. This is very difficult to do with SCRs, especially if parallel operation is a requirement. More than six transistors may be required to handle 50 hp of control. Taking a small loss in overall efficiency and an added parts count, a better applied waveshape can be obtained.

2. Various schemes have been used in the past for better waveshaping but have been set aside in favor of cost considerations. If output transformers are used for output isolation from the load, outputs can be added by series secondary connections or primary tap switching. Where only power frequency is desired the transformers can be resonated. Without output transformers, parallel offset inverters or other inverter configurations can form better waveshapes. By proper phase shifting, a six-step waveform can be applied to each leg of a three-phase system by providing a four-wire output. Still better results might be obtained by synthesis techniques. The result must be balanced against overall efficiency and reliability. Since 400-Hz transformers are smaller than 60-Hz transformers, transformer addition is less costly in weight and size than 60 Hz. The range of frequencies for the considered inverters is low enough so that switching losses can be neglected. The power dissipated in each transistor will consist primarily of conduction losses and turn-off losses. Power is also dissipated in diodes which are necessary to conduct the per phase current when the inverter transistor or GTO is turned off.

V. POWER FACTOR AND HARMONICS

A. HARMONIC POWER LOSS. If the output contains a large portion of harmonic power and the load cannot utilize this power, such as AC motors or transformers, losses occur in the loads. Power losses taken in the rectification and voltage waveform control processes limit the overall efficiency, losses in the loads can be more significant.

1. POWER FACTOR AND HARMONICS

a. Power factor is the ratio of real power to apparent power. This ratio includes the effects of harmonic components of current and voltage and the phase displacement between current and voltage. The resulting poor power factor (60%) of most switching supplies is produced by the large harmonic currents in the input. In this case, the only way of improving the power factor is to reduce or eliminate the input current's line harmonics.

b. In comparison with switching mode supplies, the linear supplies power factor is 79.6 percent. The input section of the linear supply looks quite similar to that of a switching supply, but the isolating 60-Hz transformer of the linear supply produces two effects that reduce even harmonics, particularly where symmetrical circuitry exists, and improve the power factor. If the third, fifth, and seventh harmonics were removed, the power factor would improve. Four means for removing or reducing these harmonics are: phase multiplication through proper three-phase application of multiple supplies; three-phase input design; AC-input passive filtering of low-frequency harmonics; and active filtering of the input.

2. THREE-PHASE INPUT. Switch-mode power supplies with three-phase input-filter circuits have excellent power factors, but are practical only where the end user has three-phase power available. The input is simply a three-phase rectifier bridge with a bulk inductor-capacitor (IC) filter. The filter produces added power loss. With this approach, the third harmonic and all multiples are cancelled, and the harmonic currents decrease at a rate of $1/N$, where N is the harmonic number.

B. ELECTROMAGNETIC INTERFERENCE AND LOW-FREQUENCY HARMONICS. Most of the emphasis in reducing the electromagnetic interference of switch-mode power supplies centers on removing the higher-frequency transient input harmonics of the switching or inverter frequency from the input power lines, but lower-frequency, line-generated harmonics, below 20 kHz, should not be overlooked. These lower-frequency harmonics can produce several adverse effects: distortion of the AC line-voltage waveshape that may affect operation of other equipment on the same line; poor power factor, requiring over-sizing the AC supply system and possible utility-rate penalties; high telephone influence factor (TIF), which may affect voice or data-communications lines.

1. INPUT IMPEDANCE. Lower-frequency line harmonics, multiples of the input frequency, are generated by the input rectification and filtering section. In many cases, the limiting impedance to input current is the AC source. Low input impedance causes very narrow conduction times. This produces extremely high harmonic content in the input currents. Phase multiplication is of

particular value where multiple supply sources feed a large load. Harmonic-current filtering with passive elements is not usually practical for lower-frequency line-harmonic attenuation. A passive filter network that attenuates the third and fifth harmonics sufficiently to improve the power factor requires several large inductors and capacitors operating at low frequencies with a large power loss. It also provides inherent transient-voltage suppression and inverter-frequency EMI suppression via the series-inductor impedance. However, this inductor would add approximately 10 in.³ and one pound/1,500 watts. Many systems today require multiple-input frequency capability, which rules out the tuned passive-filter approach since it is effective for only one input frequency. However, if fixed input frequency, size, and weight do not present problems, this method could effectively correct the power factor.

2. ACTIVE FILTERS

a. Recent state-of-the-art designs include the use of active filters to control harmonic power content. These designs are not to be confused with the low-power operational amplifier active filters. There are several techniques to filter the lower-frequency harmonic line currents by applying active switching components on the AC-input side of the inverter. In the simplest form, the circuit comprises a boost switching regulator modulating the raw rectified line voltage. With proper modulation of the switching transistor, a line current containing primarily the fundamental frequency can be realized.

b. The active-filter approach, particularly when operating at higher frequencies, offers these advantages: excellent input power factor (greater than 95%), minimal size and weight increases, insensitivity to input frequency, effectiveness for single-phase input, and capability of preregulating inverter bulk voltage. Disadvantages include: greater electronic component count with resultant reduction in mean-time-between-failure (MTBF), appreciable unit-cost increase (<10%), lower efficiency, and ultra high-frequency conducted EMI. Bendix is pursuing some FY-80 R&D work on 400-Hz aircraft generators in this area.

3. EFFICIENCY. The same factors prevalent in the rectification and switching of the input of a supply are present in the outputs of inverters. The same techniques can be applied at the output to reduce output harmonic contents. Efficiencies of six-step inverters are approximately 60%. This is poor for high-power use. Switching supplies which improve the waveform, such as the 12-step, 15-kw unit built by Delco Electronics for the U.S. Army, Fort Belvoir, VA, R&D contract No. DAAK-70-77-C-0157, approaches 75%. Recently designed computer controlled pulse width modulation, AC motor 60-Hz controls claim 94% of the line-power input delivered to the load. This may be a sample of "specmanship" as most of the power loss of this type of control occurs in the load. A goal of 80% is presently being sought. See their Final Report R80-142, October 1980.

4. DISTORTION. Total harmonic distortion goal is frequently set at less than 5% under any operating condition. This is a rather stringent requirement. Class B audio amplifiers frequently have harmonics in this range. A requirement of 6 to 8% would be more realistic at this time.

5. CONCLUSION. The low-frequency AC input and output harmonic currents generated by switch-mode power supplies should be recognized as a potential

problem for some applications. Viable solutions exist for reducing or eliminating these harmonics. Key system parameters should be established when designing systems that use power switching: total system power requirement, input-frequency variation, availability of three-phase power, importance of size, weight, efficiency, cost, and system susceptibility to low-frequency interference. The most valuable parameters should be stressed and relief given in other areas where the parameters are not as important. The proper circuit technique should then be selected based on these parameters.

VI. STATE OF TECHNOLOGY

A. SOLID-STATE SWITCHING. Solid-State switching promises great reductions in weight and frequency flexibility over present 400-Hz sources. Switching supplies, AC motor control by adjustable frequency, aircraft 400-Hz supplies, and pulse-width power modulation are all forms of power switching and have common problems. High-power, high-voltage switching transistors have just begun to attack the 25-kva power region. The advent of the low-cost microcomputer has freed electronics designs from the dependence on accurate line frequency control for trigger generation. The fleet still maintains a large amount of equipment that relies upon servos and servo controllers for position detection and alignment. New digital techniques employing stepping motors, magnetic pulse pickup, and electronic logic manipulation, are more accurate. As these systems become more numerous, the need for stable power frequency synchronization will be less of a requirement.

B. MICROCOMPUTER. The use of a microcomputer for 400-Hz power generation by inverter action would eliminate the need for self-synchronous or self-commutating designs. Pulse width, pulse complexity, and pulse modification can be performed by software and stored in a programmable read only memory (PROM). With the high-frequency crystal as the reference and large-scale integration counters and dividers, triggers can be generated with a high degree of accuracy. If required, a hold-off bias pulse can be software formed.

1. HARDWARE. Although the circuit complexity is greater, the reliability of large-scale integrated circuits is high and the reliability of the overall system may not be unduly affected. The need for speed in the microcomputer compared to the required 400-Hz period response is not great. Many hardware shortcomings can be corrected by a software modification. With expanded memory, sensing and control can be accomplished by the same computer establishing hardware waveform generation if PROM chips are kept separate. Control changes should not unduly affect basic hardware operation. The use of biased transistors and optical isolation should reduce the danger of cascading failures due to cross conduction.

2. SUPPLY APPROACH. Since 60-Hz transformers are heavy and large, a 400-Hz solid-state inverter, fed from a DC link, probably would be better if isolation transformers were not incorporated on the input. Protection devices and multiphase, 6-diode 3-phase rectification may provide sufficient input line transient isolation. Transformers on the 400-Hz output, however, would be much smaller, provided a common isolated load for pulse addition, and help filter out low-frequency harmonics from the output. This technique has merit and should be considered. To reduce harmonic power loss, a 12- to 24-step output waveform optimized by microcomputer control for best wave filtering or equal power transfer to form the output sine wave should be considered. The "six-step" inverter is too coarse for general utility power use, efficiency will be low even with harmonic filtering.

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