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HIGH FREQUENCY LIGHTING SYSTEMS. REVIEW OF PREVIOUS SYSTEMS PERFORMANCE RECORDS. PROPOSAL FOR OPTIMUM SYSTEM ANTHOLOGY -BIBLIOGRAPHY

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Author
Campbell, J.H.

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HIGH FREQUENCY LIGHTING SYSTEMS

Review of Previous Systems Performance Records
Proposal for Optimum System Anthology - Bibliography

John H. Campbell

June 1979

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HIGH FREQUENCY LIGHTING SYSTEMS

REVIEW OF PREVIOUS SYSTEMS
PERFORMANCE RECORDS
PROPOSAL FOR OPTIMUM SYSTEM
ANTHOLOGY - BIBLIOGRAPHY

JOHN H. CAMPBELL

Energy Efficient Lighting Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California
94720

JUNE 1979

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INTRODUCTION

It is well known, as the many papers in the bibliography will show, that fluorescent and other electric discharge lamps, and ballasts become more efficient as power frequency increases. Advantage has been taken of this phenomenon in one of two ways: increased lumen output for a given input wattage or reduced input wattage for a given light output compared to the conventional 60Hz system.

When studies were first made to determine high frequency characteristics of fluorescent lamps, the lighting industry was attempting to increase illumination levels for certain commercial and industrial applications where it was badly needed to provide illumination levels for the various visual tasks.

In their book "The Science of Seeing," the authors, Drs. Luckiesh and Moss, established by comprehensive testing of human subjects, that the illumination level for a given task must be substantially doubled to produce significant improvements in seeing.

When the first high frequency systems were commercially available, the objective was to double illumination levels without doubling the overall cost compared to the 60Hz system. Much of the additional initial cost was recovered by the reduced operating cost of the system.
The main purpose of this study is to determine whether there is a sufficient gain in overall efficiency of large high frequency lighting systems to encourage development and application of such systems today. If the answer is positive, a further step can be taken toward reducing power requirements in lighting to save electrical energy.

In order to accomplish this objective it is appropriate to take the following steps:

Review past central high frequency systems for objectives, characteristics, electrical and lighting performance and reliability.

Determine whether any of these systems can be upgraded or modified through the use of present technology of new or improved switching devices, circuits and components.

Use the experience gained in the operation of previous systems and knowledge of present technology to propose a new or improved system.

Evaluate the proposed new high frequency system on the basis of an economic comparison of energy requirements and costs using presently available 60Hz systems as a base.
THE SCRUTINY OF ALL APPROPRIATE COMPONENT MANUFACTURERS
IS INVITED TO ANALYZE THE BRANCH CIRCUIT HIGH FREQUENCY
SYSTEM, PROPOSED AS A RESULT OF THIS STUDY. THE TECHNICAL
MERIT AND ECONOMIC FEASIBILITY WILL THEN BE DETERMINED BY
THE ENGINEERING, MARKETING AND MANUFACTURING DEPARTMENTS OF
THE PARTICIPATING COMPANIES.
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SUMMARY

The previous high frequency fluorescent lighting systems, using a centrally located frequency converter, were originally designed to provide higher illumination levels at a lower operating cost. This was accomplished by higher overall efficiency compared to the conventional 60Hz system in which individual magnetic ballasts located in each lighting fixture, supplied power to two or four fluorescent lamps.

These pioneering efforts over the past 27 years by the lighting industry and the consumer resulted in a variety of experiences, which have been chronicled in the following report. The first of the central systems, the 360Hz Magnetic Frequency Multiplier, accomplished the increased illumination objective, but failed to meet the projected initial cost or overall economic target. This system was then relegated to special applications such as experimental plant growth, where the conventional system could not be used because of ballast size and weight. Experience showed operational reliability to be good, but any updating of this equipment would necessarily include a 15% increase in overall efficiency to compete with other central converters.

420Hz, 840Hz Motor Generator Supply

The motor generator set with outputs of 420 or 840Hz provided reliable operation and long life with a competitive cost per kw in large sizes of 50kva or better. A 10% gain in overall efficiency of large installations using 96" T-12 slimline lamps
WAS REALIZED, COMPARED TO 60HZ CONVENTIONAL SYSTEMS.

SEVERAL APPLICATIONS OF THE 420HZ FLUORESCENT LIGHTING SYSTEMS USING MOTOR-GENERATOR SETS ARE DESCRIBED. ALL OF THESE INSTALLATIONS, INCLUDING THE FIRST ONE AT THE UNION COLLEGE FIELD HOUSE WERE INSTALLED ON A LIGHTING-PERFORMANCE-PER-DOLLAR CONSIDERATION, BASED STRICTLY ON THE ECONOMIC MERITS OF HIGH FREQUENCY LIGHTING.

PROBLEMS INVOLVED AUDIBLE NOISE EMANATING FROM THE FREQUENCY CONVERTERS AND PROPER CONVERTER LOCATION TO KEEP THE NOISE OUT OF THE LIGHTED AREA. AFTER THESE DIFFICULTIES WERE OVERCOME, THE PERFORMANCE, RELIABILITY AND ECONOMIC GAINS OF THE MOTOR GENERATOR HIGH FREQUENCY SYSTEM WERE CONFIRMED BY MANY YEARS OF SUCCESSFUL OPERATION.

PERTINENT DATA ON THE EFFICIENCY, PERFORMANCE AND ECONOMICS OF THE MAJOR INSTALLATIONS ARE COVERED IN THIS REPORT AND AC-COMPANYING REFERENCES.

MOTOR-GENERATOR HIGH FREQUENCY SYSTEMS WERE ABANDONED WHEN BALLASTS BECAME DIFFICULT TO OBTAIN AND THE ANNOUNCEMENT OF POWER TRANSISTORS AND SILICON CONTROLLED RECTIFIERS PREDICTED HIGHER EFFICIENCY LIGHTING SYSTEMS.

420HZ GAS TURBINE GENERATOR SYSTEMS

TOTAL ENERGY, GAS TURBINE GENERATOR SYSTEMS USING 420HZ POWER FOR LIGHTING, HAVE A RELATIVELY LOW COST PER KWH BECAUSE THE EXHAUST GASES ARE USED FOR VARIOUS HEAT APPLICATIONS AND
AIR CONDITIONING. A study of one of the largest installations of this system at the Northern Illinois Gas Company shows the lighting system to be highly reliable, lower in initial and operating cost and higher in overall efficiency than the conventional 60Hz system. Slimline (instant start) 48" T-12 and 96" T-12 lamps, with low cost, high efficiency ballasts are used throughout. Approximately 1100KW of the power generated is used in the high frequency lighting system. Voltage required to start and operate the lamps is distributed to the fixtures. Wire size and type is the same as would be used at 60Hz for equivalent current.

Life tests reported after the first 5 years of operation show considerably increased lamp and ballast life for the 420Hz system compared to the 60Hz control test.

Due to the large blocks of power involved and with generators located on the turbine shaft, the total energy or co-generation systems must remain as a central power supply. Power frequency for distribution over long lines will then be limited to prevent high losses and expensive wiring.

One system disadvantage is that when only small increments of power are needed, the turbine must continue to operate. Apparently the overall economy at full load, more than overcomes this deficit. A visit to this facility in 1978 showed that there was no audible noise due to the high frequency system even in low ambient level offices.
CAPACITORS ARE USED EXCLUSIVELY AS BALLASTS TO OPERATE 48" T-12, AND 96" T-12 SLIMLINE INSTANT START LAMPS IN 3 OFFICE BUILDINGS WITH A TOTAL LIGHTING LOAD OF 1100KW AT A FREQUENCY OF 420HZ.

THE GAS TURBINE TOTAL ENERGY POWER SUPPLY COUPLED WITH A 420HZ GENERATOR AND LOW COST FIXTURES, MUST BE CONSIDERED AS AN ECONOMICAL ENERGY EFFICIENT SYSTEM. SEVERAL OTHER INSTALLATIONS OF GAS TURBINE GENERATORS WITH 420 AND 840HZ LIGHTING WERE INSTALLED IN VARIOUS PARTS OF THE COUNTRY. ADDITIONAL APPLICATIONS OF THIS TYPE WILL NOW AWAIT AN ADEQUATE GAS SUPPLY.

SILICON CONTROLLED RECTIFIER 3000HZ FREQUENCY CONVERTER

THE ELECTRONIC 3000HZ FREQUENCY CONVERTERS PROVIDED POWER IN SIZES OF 20 AND 40KW. THIS SYSTEM WAS DEVELOPED SOON AFTER THE SILICON CONTROLLED RECTIFIER WAS ANNOUNCED AND TRIAL INSTALLATIONS WERE STARTED IN THE EARLY 1960'S. THIS SYSTEM WAS DESIGNED FOR COMMERCIAL LIGHTING USING THE STANDARD 40 WATT RAPID START LAMP. LIGHTING FIXTURES CONTAINING FOUR-LAMP CAPACITOR BALLASTS AND PREHEAT TRANSFORMERS PROVIDED HIGH OVERALL EFFICACY. THE GAIN IN SYSTEM EFFICACY WAS 14% TO 18% DEPENDING ON WHETHER CATALOG LUMENS OR MINIMUM ALLOWABLE LUMENS WERE USED AS THE 60HZ BASE. A NUMBER OF INSTALLATIONS TOTALING APPROXIMATELY 1500 KILOWATTS WERE MADE IN A VARIETY OF APPLICATIONS.

IF ALL OF THE SYSTEM SPECIFICATIONS WERE FOLLOWED TO THE 'LETTER' SOME OF THE PERIPHERAL PROBLEMS SUCH AS AUDIBLE NOISE
AND SLOW STARTING OF LAMPS COULD BE AVOIDED. NOISE GENERATED IN THE WIRING AND IN THE PREHEAT TRANSFORMERS OF THE BALLASTS WAS THE MOST PREDOMINANT COMPLAINT IN THE EARLY APPLICATION OF 3000Hz LIGHTING, THE COMPLEX NATURE OF THE FREQUENCY CONVERTERS ALSO RESULTED IN MAINTENANCE PROBLEMS AND ADJUSTMENTS WHICH WERE DIFFICULT TO MAKE IN LOCATIONS WHERE THERE WERE NO QUALIFIED OR KNOWLEDGEABLE PERSONNEL.

THE TEST INSTALLATION MADE AT THE OHIO POWER COMPANY IN 1967 WAS USED TO DEMONSTRATE FLUORESCENT LIGHTING USING THIS ENERGY EFFICIENT SYSTEM, BUT WAS REMOVED IN NOVEMBER OF 1978 DUE TO THE HIGH COST OF REPLACEMENT PARTS, WHICH BY THEN HAD BECOME OBSOLETE.

WESTINGHOUSE DESIGNED A SIMILAR S.C.R. 3000Hz SYSTEM. EACH FREQUENCY CONVERTER WAS RATED AT 35KVA AND PRODUCED A SQUARE CURRENT WAVE FORM. A PROTOTYPE SYSTEM WAS INSTALLED IN A SUPERMARKET IN WHICH 2 CONVERTERS SUPPLIED A FLUORESCENT LAMP LOAD OF 60KW. SOME DIFFICULTY WAS EXPERIENCED IN SWITCHING THE LAMP LOAD IN 4 INCREMENTS WITH RESULTING CONVERTER MAINTENANCE. AUDIBLE NOISE FROM THE OPEN STRIP TYPE FIXTURES ALSO BECAME A PROBLEM AND THE INSTALLATION WAS REMOVED AFTER ABOUT ONE YEAR OF SERVICE.

MODULAR, BRANCH CIRCUIT HIGH FREQUENCY SYSTEM

A BRANCH CIRCUIT HIGH FREQUENCY MULTI-FIXTURE SYSTEM IS A PROPOSAL DESCRIBED IN THE FOLLOWING REPORT. THIS ARRANGEMENT WILL ELIMINATE THE MAJOR PROBLEMS ASSOCIATED WITH LARGE CENTRAL POWER
SUPPLIES AND PROVIDE A COST EFFECTIVE SYSTEM WITH A HIGHER OVERALL EFFICIENCY. AUDIBLE NOISE IN THE LIGHTED AREA, ASSOCIATED WITH SOME PREVIOUS HIGH FREQUENCY SYSTEMS IS ELIMINATED BY GENERATING AND DISTRIBUTING POWER FREQUENCIES ABOVE THE HUMAN HEARING RANGE. DISTRIBUTION OF POWER TO THE FLUORESCENT LIGHTING FIXTURES IS ACCOMPLISHED FROM 'LOAD CENTER', PROVIDING A FOUR-WAY SHORT LINE DISTRIBUTION OF 50 TO 75 FT. DEPENDING UPON LOAD REQUIREMENTS.

THE CONCEPT FEATURES D.C. DISTRIBUTION TO EACH OF THE BRANCH CIRCUIT 'LOAD CENTER' INVERTERS HAVING A CAPACITY OF 5 TO 15 KILOWATTS.

DUE TO RECENT IMPROVEMENTS IN POWER TRANSISTOR TECHNOLOGY, THE INVERTERS CAN BE DESIGNED FOR POWER EFFICIENCIES OF 92 TO 95% DEPENDING ON OUTPUT CAPACITY. CALCULATIONS SHOW AN INCREASE IN SYSTEM EFFICIENCY OF 34% IN LUMENS PER WATT USING A 5KW INVERTER, COMPARED TO 60HZ-2-LAMP 40 WATT RAPID START BALLASTS. IF THE PREMIUM HIGH EFFICIENCY 60HZ-2-LAMP 40 WATT BALLASTS ARE USED AS A BASE, THE GAIN FOR THE HIGH FREQUENCY SYSTEM IS 18%.

LIGHTING FIXTURES CAN BE EQUIPPED WITH EITHER RAPID START LAMPS AND BALLASTS OR INSTANT START SLIMLINE LAMPS. THE INSTANT START SYSTEM IS PREFERRED FROM THE STANDPOINT OF SIMPLICITY, BUT LAMP COST IS SOMEWHAT HIGHER. IN EITHER CASE SMALL, LIGHT WEIGHT LOW LOSS CAPACITOR BALLASTS ARE USED IN EACH FIXTURE, MAKING FEASIBLE A RE-DESIGN OF FLUORESCENT FIXTURES WITH LESS METAL, OR WITH METAL SUBSTITUTES SUCH AS EXTRUDED PLASTIC. FIXTURE WIRING
IS ALSO GREATLY SIMPLIFIED. FIXTURE WEIGHT AND CORRESPONDING SHIPPING EXPENSE WILL BE REDUCED, SO A LOWER COST FIXTURE IS AN ANTICIPATED ECONOMIC GAIN FOR THE BRANCH CIRCUIT CONCEPT.

TABLE I IN THE REPORT SHOWS AN ECONOMIC COMPARISON WITH 60HZ STANDARD AND 60HZ HIGH EFFICIENCY BALLASTS AS A BASE. FREQUENCY CONVERTER COSTS, WHICH INCLUDE D.C. COMPONENTS IN THE DISTRIBUTION SYSTEM ARE ESTIMATED TO BE $200 TO $300 PER K.W. DEPENDING UPON INVERTER SIZE (10Kw OR 5Kw).

IT IS THOUGHT THAT THIS HIGH FREQUENCY SYSTEM CONCEPT WILL APPLY TO LARGE NEW APPLICATIONS WHERE A COMPLETE SYSTEMS APPROACH AND AN ENGINEERED PACKAGE CAN BE OFFERED AS AN INDEPENDENT LIGHTING SYSTEM IN A WAY SIMILAR TO THE INSTALLATION OF AN AIR CONDITIONING SYSTEM WITH ITS ASSOCIATED COMPONENTS.

THE BRANCH CIRCUIT SYSTEM CAN BE CONSIDERED AS A SUPPLEMENTARY TO THE ENERGY EFFICIENT ELECTRONIC BALLASTS, RECENTLY DEVELOPED AND SUCCESSFULLY DEMONSTRATED IN A PACIFIC GAS AND ELECTRIC BUILDING IN SAN FRANCISCO. These ballasts provide a direct replacement for the less efficient conventional ballasts used in present fluorescent lighting fixtures.
HIGH FREQUENCY LIGHTING SYSTEMS

(A CHRONOLOGICAL ACCOUNT OF THE DEVELOPMENT, APPLICATION AND PERFORMANCE OF HIGH FREQUENCY LIGHTING SYSTEMS)

59. The development of fluorescent ballasts using the sequence starting series operating circuit, saved half of the copper and iron and reduced ballast losses by 50%. During World War II, ballasts using this circuit to operate four 100 watt T-17 lamps were used extensively in industrial plants throughout the United States. After the war, the series sequence circuit was applied to slimline lamp ballasts and subsequently to most all rapid start ballasts. It soon became apparent that the point of diminishing returns had been reached in circuit development for magnetic ballasts on conventional 60Hz power.

Lamp and ballast characteristic tests using higher frequencies started before the war, were resumed in 1946. The results of these tests were reported in a paper presented at the National Technical Conference of the Illuminating Engineering Society in 1947. The basic advantages in the operation of fluorescent lamps on higher frequency power were shown to be: increased lamp and ballast efficiency, smaller, lighter weight ballasts and greatly reduced stroboscopic effect.

While fundamental studies of lamp and ballast characteristics were in process, a frequency converter to provide the required power was being developed.

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HIGH FREQUENCY POWER SUPPLIES

MAGNETIC FREQUENCY CONVERTER

The General Electric Co. acted quickly to provide an experimental harmonic generator which converted three-phase 60Hz power to 540Hz power. The circuit is an adaptation of ignitor excitation systems and is essentially a harmonic generator in which the resonant circuit in parallel with the load is tuned to the ninth harmonic of 60Hz.

A paper describing the system was presented to the National Electronics Conference in 1947 along with a demonstration of the converter operating a bank of fluorescent lamps. This specific circuit had some regulating problems from full load to half load and was not applied commercially. However, this development served as a forerunner to the Magnetic Frequency Multiplier which soon followed.

MAGNETIC FREQUENCY MULTIPLIER

The desire to provide a frequency changer without moving parts which could be treated as a transformer, resulted in the development of the Magnetic Frequency Multiplier. It was also desirable to simplify the ballast and increase the system efficiency.

The magnetic frequency multiplier had a conventional 480V three phase 60Hz input with a 360Hz triangular voltage output. Fig. 1 shows the basic circuit consisting of 3 stages, a tripler (60-180Hz), a doubler (180-360Hz) and a limiter to provide load current control and proper wave form. When capacitor ballasts
ARE USED, THE TRIANGULAR VOLTAGE WAVE AT 360HZ PRODUCES A SQUARE LAMP CURRENT WAVE FORM WHICH RESULTS IN A LAMP EFFICACY CLOSE TO THAT PRODUCED BY A 20KHz SINE WAVE. FIGURES 2 AND 3 ILLUSTRATE THIS RELATIONSHIP ON A 40 WATT T-12 FLUORESCENT LAMP. FIG. 4 IS A PHOTOGRAPH OF THE 5K.W. FREQUENCY MULTIPLIER. IT WAS SUBSEQUENTLY MADE IN A 25K.W. SIZE.

APPLICATIONS

THE FIRST APPLICATION OF THE 360HZ LIGHTING SYSTEM WAS AT THE UNITED STATES DEPARTMENT OF AGRICULTURE IN BELTSVILLE, MARYLAND, WHERE TWO 5K.W. UNITS WERE INSTALLED. THE CHARACTERISTICS OF THE SYSTEM WERE IDEAL FOR OPERATING THE 96 T-8 FLUORESCENT LAMPS IN THEIR EXPERIMENTAL PLANT GROWTH CHAMBERS. FIG. 5 SHOWS THE CONCENTRATION OF LAMPS IN THE ROOM AND THE 60HZ BALLASTS LOCATED IN THE HALLWAY IN AN EARLIER INSTALLATION. TO BRING POWER TO THE LAMPS, A CABLE OF 124 WIRES WAS REQUIRED. WHEN THE 360HZ SYSTEM WAS INSTALLED ONLY 2 WIRES WERE NEEDED. THREE OUNCE CAPACITOR BALLASTS REPLACED THE 14 POUND 60HZ BALLASTS AS SHOWN IN FIG. 5. DUE TO THE SMALL SIZE OF THE CAPACITORS THEY COULD BE LOCATED IN THE ROOM AT EACH LAMP. A SINGLE POTENTIOMETER ON THE CONVERTER PANEL COULD BE USED TO ADJUST THE LOAD CURRENT FOR ILLUMINATION LEVELS OF 1600 TO 2400 FOOT CANDLES. IT HAS BEEN LEARNED FROM THE U.S. DEPT. OF AGRICULTURE THAT THE MAGNETIC FREQUENCY MULTIPLIER WAS REPLACED IN 1976 AFTER 21 YEARS OF SERVICE. MANY SIMILAR INSTALLATIONS WERE MADE IN AGRICULTURAL DEPARTMENTS OF UNIVERSITIES AND EXPERIMENTAL GROWTH CHAMBERS OF DuPONT De NEMOURS CO.

A PROTOTYPE COMMERCIAL INSTALLATION WAS MADE AT A GENERAL
ELECTRIC Co. CAFETERIA. THE DESIRED LIGHTING LEVEL WAS SET WITH THE LIMITING CONTROL OF THE FREQUENCY CONVERTER ADJUSTED FOR MINIMUM LIGHT OUTPUT. AS LAMPS AND REFLECTORS DEPRECIATED, THE CONTROL WAS ADVANCED TO PROVIDE A 100% MAINTAINED ILLUMINATION LEVEL. (FIG. 6)

EXPERIENCE

THE MAGNETIC FREQUENCY MULTIPLIER WAS A RELIABLE GENERATOR WITH MOST MAINTENANCE CONFINED TO AN INFREQUENT FAILURE OF THE SELENIUM RECTIFIER. THE SYSTEM HAD MANY FEATURES WHICH WOULD BE DESIRABLE TODAY, PARTICULARLY THE POWER MANAGEMENT BY MEANS OF A SINGLE CONTROL. IT WAS ANTICIPATED THAT THE 25K.W. SIZE WOULD HAVE A COST PER K.W., COMPETITIVE WITH CONVENTIONAL BALLASTING FOR COMMERCIAL APPLICATIONS. HOWEVER, IT WAS NOT COMPETITIVE ON FIRST COST WITH THE CONVENTIONAL 40 WATT T-12 60HZ BALLAST SYSTEM WHICH BY THIS TIME WAS IN VERY HIGH PRODUCTION. APPLICATION WAS THEREFORE CONFINED TO INSTALLATIONS WITH SPECIAL REQUIREMENTS, SUCH AS EXPERIMENTAL PLANT GROWTH.

MOTOR GENERATOR FREQUENCY CONVERTERS

IN ORDER TO EXPLOIT THE ADVANTAGES OF HIGH FREQUENCY LIGHTING FOR COMMERCIAL APPLICATIONS, MOTOR GENERATOR FREQUENCY CONVERTERS WERE DESIGNED BY GENERAL ELECTRIC TO PROVIDE THE FLUORESCENT LAMP REQUIREMENTS. THE COST PER K.V.A. IN SIZES OF 25 K.V.A. OR ABOVE WERE ABOUT EQUAL TO THE INITIAL COST PER K.V.A. OF THE CONVENTIONAL SLIMLINE 60HZ BALLASTS. THE INSTALLATION COST OF THE 420HZ FREQUENCY CONVERTER WAS MORE THAN OFFSET BY THE SAVINGS IN WIRING.
DUE TO THE 600/300 VOLT DISTRIBUTION FROM THE GENERATOR. IN ADDITION TO THE INCREASED EFFICACY OF THE FLUORESCENT LAMP, THE BALLAST WEIGHT AND WATTAGE HAS BEEN REMOVED FROM THE LIGHTING FIXTURE AND PLACED IN THE POWER SUPPLY WHICH SERVES THREE FUNCTIONS; AS A FREQUENCY CHANGER, TRANSFORMER AND VOLTAGE REGULATOR.

64 420 CYCLE BALLASTS WERE AVAILABLE FOR SEVERAL SLIMLINE (INSTANT START) LAMPS IN LAMP WATTAGE LEVELS OF 38 TO 90 WATTS AND FOR THE HIGH OUTPUT LAMPS OF THE RAPID START TYPE AT 125 TO 200 WATTS PER LAMP. THE SIMPLIFIED BALLAST CONSISTED OF A CHOKE COIL TO OPERATE ONE LAMP AND A CAPACITOR FOR THE OTHER. THIS COMBINATION PROVIDED A NEAR UNITY POWER FACTOR. NO TRANSFORMER WAS REQUIRED IN THE BALLAST OR THE LINE SINCE VOLTAGE FOR STARTING AND OPERATING THE LAMPS WAS PROVIDED BY THE GENERATOR.

THE POWER FROM THE MOTOR-GENERATOR IS DISTRIBUTED THROUGH A CONVERTIBLE CIRCUIT BREAKER PANEL BOARD TO BRANCH CIRCUITS RUN IN CONDUIT TO POINT OF USE AT INDIVIDUAL LUMINAIRES. THIS PANEL BOARD IS A STANDARD UNIT DESIGNED FOR MAXIMUM 600 VOLT A.C. SERVICE.

APPLICATIONS

UNION COLLEGE

8 THE FIRST LARGE SCALE APPLICATION OF HIGH FREQUENCY FLUORESCENT LIGHTING WAS ENGINEERED FOR THE UNION COLLEGE FIELD HOUSE IN SCHENECTADY, NEW YORK. A NEW SPORTS ARENA, THE ALUMNI MEMORIAL FIELD HOUSE WAS ERECTED IN 1954. IT ENCOMPASSES AN AREA OF APPROXIMATELY 44,000 SQUARE FEET. A MAINTAINED LEVEL OF 46 FOOT-CANDLES REQUIRED 490-96" T-12 SLIMLINE LAMPS PROVIDING A TOTAL OF

-17-
2,940,000 LUMENS.

A RATHER UNIQUE, RELATIVELY LIGHT-WEIGHT FIXTURE HOUSING FOURTEEN 96" T-12 LAMPS WAS ESPECIALLY DESIGNED FOR THIS HIGH BAY INSTALLATION. IT IS THOUGHT TO BE THE LARGEST SUSPENDED FLUORESCENT FIXTURE. IT WAS MADE PRACTICAL BY THE LIGHT WEIGHT OF THE 420Hz BALLASTS. (FIG. 7)

DUE TO THE LONG LIFE OF THE FLUORESCENT LAMP IT WAS DECIDED TO REPLACE THE LAMPS AS A GROUP EVERY 2 YEARS. UNFORTUNATELY, THE BUDGET DID NOT PROVIDE FOR THE COST OF HANGERS TO PERMIT THE LOWERING OF THE FIXTURES FOR LAMP REPLACEMENT. CONSEQUENTLY, THE FIRE TRUCK WITH EXTENSION LADDERS WAS CALLED UPON TO PROVIDE THIS FUNCTION.

POWER FOR THE LAMPS WAS PRODUCED BY TWO 30K.W. MOTOR GENERATOR SETS WITH A DOUBLE-DELTA WINDING WITH ALL THREE MID-POINT LEADS BROUGHT OUT TO A TERMINAL BLOCK SO THAT THE MIDPOINT OF EACH PHASE CAN BE GROUNDED. THIS SINGLE PHASE CONNECTION MIDTAPPED TO GROUND WAS NECESSARY TO MEET THE NATIONAL ELECTRICAL CODE REQUIREMENTS. (FIGS. 8A,8B,9A,10). THE TWO FREQUENCY CONVERTERS WERE LOCATED IN A SMALL ENCLOSURE AT ONE END OF THE BUILDING INTERIOR.

EXPERIENCE

10 THIS PIONEERING EFFORT TO MAKE USE OF A NEW LIGHTING SYSTEM WAS INSTALLED ON A STRICTLY LIGHTING-PERFORMANCE-PER-DOLLAR CONSIDERATION. IT WAS A FORERUNNER FOR MANY OTHER APPLI-
CATIONS FOUND IN INDUSTRY AND COMMERCE.

THE UNION COLLEGE INSTALLATION WAS IN OPERATION FOR 21 YEARS. IN A TELEPHONE INTERVIEW WITH THE DIRECTOR OF PHYSICAL PLANTS AT THE COLLEGE, IT WAS LEARNED THAT FOR MANY YEARS THE INSTALLATION WAS RELATIVELY FREE OF MAINTENANCE PROBLEMS. HOWEVER, IN THE LAST FEW YEARS, THE BASIC DIFFICULTY HAS BEEN CONDENSATION OF MOISTURE AROUND THE FIXTURE. THE CLAY FLOOR WAS TREATED PERIODICALLY WITH CALCIUM CHLORIDE. CONDENSATION CONTAINING THIS CHEMICAL PERMEATED AND CORRODED THE FIXTURES AND ASSOCIATED BALLASTS CAUSING FAILURES. BALLASTS WERE DIFFICULT TO REPLACE BECAUSE OF THE EXTENSION LADDER MAINTENANCE SYSTEM AND THE BALLASTS ARE NOW OBSOLETE AND DIFFICULT TO OBTAIN. THE HIGH FREQUENCY SYSTEM PER SE' IS NOT BEING BLAMED.

REPLACEMENT HAS BEEN MADE WITH A MODERN H.I.D. 60HZ LIGHTING SYSTEM WITH A NEWLY INSTALLED CAT-WALK FOR EASY LAMP AND FIXTURE MAINTENANCE.

WAKEFIELD CO., ELYRIA, OHIO

THE WAKEFIELD CO. IN VERMILLION, OHIO, MANUFACTURERS OF LIGHTING FIXTURES MADE A NUMBER OF INSTALLATIONS OF HIGH FREQUENCY LIGHTING SOON AFTER THE GENERAL ELECTRIC CO.'S 420HZ SYSTEM WAS IN OPERATION AT THE UNION COLLEGE FIELD HOUSE. WAKEFIELD'S SYSTEM EMPLOYED MOTOR GENERATOR SETS MADE BY THE GENERATOR CORP. OF 30 K.V.A. CAPACITY TO PRODUCE 840HZ. THE DISTRIBUTION AND GENERATOR WINDINGS WERE CONNECTED IN THE SAME WAY AS THAT OF THE 420HZ SYSTEM, BUT VOLTAGE FROM EACH PHASE WAS 400/200 TO MEET THE
STARTING AND OPERATING REQUIREMENTS OF THE 48" T-12 SLIMLINE LAMPS USED IN THE FIRST INSTALLATIONS. Increasing the frequency to 840Hz, resulted in an increase in lamp efficacy and a smaller more compact generator. (Figs. 11 and 12). Lamp ballasting was accomplished by means of a simple capacitor connected in series with each lamp. Power factor correction was accomplished by means of an air core reactor located in each branch circuit to add the inductance needed to correct the distribution circuits to approximately unity power factor.

The installation at the Wakefield facility was the first office building to be lighted with high frequency power. (Fig. 13, 14). 580, 48" T-12 slimline lamps were installed in a modular lighting scheme to provide an average illumination level of approximately 100 footcandles. Several additional installations of 840Hz lighting were made following this prototype application.

EXPERIENCE

After a few minor problems involving the power factor correcting reactors, the system was in satisfactory operation for many years.

Economy is the main reason for the high frequency and high voltage system of lighting. Initial cost was lower, due to the use of small capacitor ballasts as compared with the conventional 60Hz ballasts. Wattage of the system was reduced by taking advantage of the increased light output per system watt. Wattages
CAN BE DECREASED FOR A SPECIFIED ILLUMINATION LEVEL. THE VIRTUAL ELIMINATION OF BALLAST WATTS LOSS ALSO REFLECTS A SAVING IN AIR CONDITIONING CAPACITY AND EQUIPMENT. IT IS CLAIMED THAT ONLY 25 TONS OF AIR CONDITIONING WAS REQUIRED FOR THE OFFICE INSTALLATION COMPARED TO 30 TONS WHICH WOULD HAVE BEEN REQUIRED WITH THE CONVENTIONAL 60Hz SYSTEM. BALLAST HUM (120Hz) OF CONVENTIONAL BALLASTS WAS FREQUENTLY A PROBLEM IN QUIET AMBIENTS SUCH AS PRIVATE OFFICES. IT IS MENTIONED IN THE REFERENCED REPORT THAT NOISE WAS ELIMINATED IN THE 840Hz SYSTEM THROUGH THE USE OF CAPACITOR BALLASTS. HOWEVER, IN A RECENT INTERVIEW IT WAS LEARNED THAT NOISE SUBSEQUENTLY DEVELOPED AND BECAME PROGRESSIVELY HIGHER AND NOTICEABLE IN THE PRIVATE OFFICES WHERE AMBIENT NOISE FROM OTHER SOURCES WAS LOW. IT WAS ALSO REPORTED THAT SOME DIFFICULTIES WERE EXPERIENCED IN STARTING LAMPS WHEN INTERIOR TEMPERATURES WERE LOW.

Many of the 840Hz components became obsolete and the system was replaced with modern 60Hz fluorescent lighting in 1976 after 20 years of service.

NORTHERN ILLINOIS GAS CO., AURORA, ILLINOIS

IN 1962 THE NORTHERN ILLINOIS GAS CO. INSTALLED SEVERAL TOTAL ENERGY SYSTEMS TO PROVIDE LIGHT, HEAT AND AIR CONDITIONING IN 3 BUILDINGS OF THEIR AURORA ILLINOIS FACILITY. THE GAS TURBINES WERE USED TO DRIVE BOTH 60Hz AND 420Hz GENERATORS. THE TOTAL 420Hz POWER FOR LIGHTING THE 3 BUILDINGS IS APPROXIMATELY 1100K.W. NONE OF THE ELECTRICAL POWER IS USED FOR HEATING OR AIR CONDITIONING, SINCE THE WASTE EXHAUST HEAT IS UTILIZED FOR THE LATTER TWO
FUNCTIONS. The cost of electric power is therefore, relatively low.

In the Northern Illinois Gas buildings, most of lighting K.V.A. is for office illumination with a small fraction for research laboratory, hallways, and cafeteria.

All 420Hz lighting fixtures contain only capacitor ballasts operating 48" T-12 slimline lamps or 96" T-12 slimline lamps. At the time the 420Hz capacitor ballasts were installed, the cost was less than one third the cost of an equivalent 60Hz conventional ballast. The capacitor ballasts operate two lamps in series sequence which also simplifies the fixture wiring (Figs. 15, 16).

The distribution of power employed at the Northern Illinois Gas Co. facility is a dual system in which air handling, computers and other devices are handled with a 60Hz riser and lighting on a 420Hz riser. In the office buildings lighting and power loads are divided on an approximate 60/40 ratio. With 420Hz power reducing the lighting load by 25%, the current carrying capacity of the two risers may be reduced over that required for a single riser in a complete 60Hz system.

The system economy is further improved by distributing the high voltage required to start both 48" T-12 and 96" T-12 slimline lamps, thus saving on wiring cost and eliminating the transformer at each fixture. (Figs. 17 & 18)

Capacitor ballasts have negligible losses so system efficiency which includes the ballast loss can be considerably higher at 420Hz. Comparisons calculated by Northern Illinois Gas showed an overall increase of 47% with 48" T-12 slimlines at 420Hz compared
TO THE SAME LAMPS OPERATING ON 60Hz BALLASTS. HOWEVER, IF THE RAPID START F-40 T-12 LAMP AND CORRESPONDING MAGNETIC BALLAST IS USED AS A 60Hz BASE SYSTEM, THE INCREASE IN OVERALL EFFICIENCY WOULD HAVE BEEN ABOUT 22% FAVORING THE 420Hz SLIMLINE. IF CURRENT LUMEN FIGURES FOR 35 WATT RAPID START LAMPS AND PREMIUM HIGH EFFICIENCY 60Hz BALLASTS ARE USED AS A BASE, THE DIFFERENCE IN OVERALL EFFICIENCY BETWEEN THE TWO SYSTEMS WOULD BE APPROXIMATELY 15% FAVORING THE 420Hz SLIMLINE.

ONE ADDITIONAL ADVANTAGE OF THE CAPACITOR BALLAST WHICH HAS NOT BEEN THOROUGHLY INVESTIGATED IS THE REDUCTION IN FIXTURE TEMPERATURE AS A RESULT OF THE VIRTUAL ELIMINATION OF POWER LOSS IN THE FIXTURE. LAMP BULB WALL TEMPERATURES ARE DECREASED RESULTING IN ADDITIONAL INCREASES IN LAMP EFFICACY, IF THE SYSTEM IS OPERATING IN NORMAL ROOM AMBIENT TEMPERATURES.

CAPACITOR BALLASTS ALSO RESULT IN A SIGNIFICANT REDUCTION IN AIR CONDITIONING REQUIREMENTS COMPARED TO 60Hz SYSTEMS.

ONE ANALYSIS OF THE ECONOMY OF THE TOTAL ENERGY SYSTEM GIVEN BY THE NORTHERN ILLINOIS GAS CO. IN 1967 IS AS FOLLOWS:

"A TYPICAL EXAMPLE OF THE BENEFITS IS THE BEST WAY TO DEMONSTRATE THE ECONOMICS OF SUCH A SYSTEM. ONE OF OUR BUILDINGS IS EQUIPPED WITH TOTAL ENERGY USING HIGH FREQUENCY LIGHTING. THE MAXIMUM ELECTRICAL REQUIREMENT OF THIS BUILDING IS 820 K.W., OF WHICH 310 K.W. IS 420-CYCLE LIGHTING. THE BALANCE IS FOR AIR HANDLING AND PUMP MOTORS, COMPUTER SYSTEMS AND MISCELLANEOUS
POWER REQUIREMENTS."

"AN ADDITIONAL 90 K.W. WOULD BE NEEDED TO OPERATE THIS LIGHTING SYSTEM ON 60-CYCLE POWER. THE MINIMUM COST FOR THE ADDED CAPACITY IN GENERATORS AND ENGINES ADDS UP TO $13,500. IN ADDITION, THE ENERGY NECESSARY TO OPERATE THE SYSTEM IS A NEVER-ENDING COST. IN THE 20-YEAR LIFE OF THIS EQUIPMENT, THE OPERATING COST COULD BE EXPECTED TO TOTAL $94,000. THIS ADDITIONAL EQUIPMENT AND OPERATING EXPENSE WOULD THEN EQUAL $107,500 OVER THE LIFETIME OF THE ENGINE GENERATORS."

EXPERIENCE

IN 1967, 5 YEARS AFTER THE FIRST LARGE INSTALLATION AT THE AURORA ILLINOIS FACILITY, THE FOLLOWING REPORT ON LAMP AND BALLAST OPERATION WAS MADE:

"THE STANDARD FLUORESCENT LAMP USED FOR ANY 60-CYCLE SYSTEM IS ALSO USED FOR 420-CYCLE. EXPERIENCE AT NORTHERN ILLINOIS GAS COMPANY SHOWS THAT LONGER LIFE MAY BE EXPECTED ON LAMPS USED AT THE HIGHER FREQUENCY."

"WE HAVE CONCLUDED LIFE TESTS ON THREE BUILDINGS USING THE SAME FLUORESCENT LAMP TYPE SUPPLIED BY THE SAME MANUFACTURER. THE FIRST BUILDING USES STANDARD 60-CYCLE POWER WITH SLIMLINE FLUORESCENT LAMPS. THE SECOND USES THE SAME LAMP WITH 420-CYCLE POWER AT 36 WATTS PER TUBE. THE THIRD BUILDING USES 420-CYCLE POWER, BUT USES 31 WATTS PER TUBE. TUBE LIFE IS DETERMINED BY THE POINT AT WHICH 20 PERCENT OF THE TUBES HAVE BEEN REPLACED ON
AN INDIVIDUAL BASIS. WE THEN MAKE A MASS REPLACEMENT OF ALL LAMPS IN THE BUILDING.

"THE CONTROL BUILDING USED IN THE TEST IS OUR LA GRANGE CUSTOMER SERVICE BUILDING OPERATING ON 60-CYCLE POWER. NORMAL LIFE EXPECTANCY OF THE SLIMLINE TUBES USED IN THIS BUILDING IS 7,500 HOURS, BUT WE ACHIEVED 8,360 BEFORE MASS REPLACEMENT WAS REQUIRED. OUR GENERAL OFFICE BUILDING WITH 420-CYCLE POWER IS EQUIPPED WITH SLIMLINE LAMPS OPERATING AT 36 WATTS PER TUBE. THE LAMP WATTAGE IN THESE TWO BUILDINGS IS THEREFORE EQUIVALENT, BUT A TOTAL OF 12,480 HOURS WAS ACCUMULATED ON THESE TUBES AT THE GENERAL OFFICE BEFORE 20 PERCENT HAD BEEN REPLACED. LIFE WAS THUS INCREASED BY APPROXIMATELY 50 PERCENT WHILE LIGHT OUTPUT WAS ALSO INCREASED. IN THE THIRD BUILDING, THE LAMPS USED 31 WATTS PER TUBE TO OBTAIN A LIGHT OUTPUT EQUIVALENT TO THE 60-CYCLE SYSTEM IN THE CONTROL BUILDING. THIS LOWER WATTAGE RESULTED IN A FURTHER INCREASE IN LIFE. MASS REPLACEMENT WAS REQUIRED AFTER 22,360 HOURS OF OPERATION; ALMOST THREE TIMES THE LIFE OF THE TUBES IN THE 60-CYCLE SYSTEM OF THE CONTROL BUILDING."

"AN INTERESTING SIDELIGHT OF THIS LIFE TEST WAS THE NEEDED BALLAST REPLACEMENT. THE 60-CYCLE SYSTEM REQUIRED REPLACEMENT OF 11.5 PERCENT OF THE BALLASTS IN THE 8,360 HOURS. THE GENERAL OFFICE REPORTED REPLACEMENT OF ONLY ELEVEN OF MORE THAN 3,800 BALLASTS IN THE 12,480 HOURS (LESS THAN 0.8 PERCENT). FURTHERMORE, THE 420-CYCLE BALLASTS COST $1.25, WHILE THE 60-CYCLE BALLASTS COST $7.50."
Although it was not stated in the report, an inquiry revealed that both 60Hz and the 420Hz lamps in the life test had the same number of starts, approximately 1 start for each 12 hours of burning.

When the 420Hz installation was first made, some audible noise was traced to the power factor correction coils. When these were removed from the lighted area and placed in separate compartments, the noise was eliminated. A visit to this facility by the writer in November 1978 confirmed that the lighted areas had no audible noise.

The total energy system at the Northern Illinois Gas Co. has now been in operation for 16 years and experience to date indicates that it is a technically and economically viable system, enhanced by the use of 420Hz lighting. An interview with the Managing Director of Research and Development at Northern Illinois Gas, revealed that expansion of the total energy system for general use in similar commercial and industrial application has been delayed due to the present shortage of gas supplies.

McAllen High School, McAllen, Texas

This total energy gas turbine-generator system was one of the first installations of its type completed. It has been in operation since 1963. The lighting system uses 840Hz operating 96") T-12 Slimline lamps throughout the building. One gas turbine driving a 60Hz and an 840Hz generator provides, all the power, heating and air conditioning for the building. A back-up gas
ENGINE DRIVING DUPLICATE GENERATORS IS USED INDEPENDENTLY DURING MAINTENANCE PERIODS. THE SYSTEM IS STILL IN OPERATION AND THE ARCHITECT STATES THAT THE 840HZ FLUORESCENT LIGHTING HAS SAVED MONEY OVER A CONVENTIONAL 60HZ SYSTEM FROM AN EFFICIENCY STAND-POINT. HOWEVER, THE BALLASTS BECAME OBSOLETE SEVERAL YEARS AGO. NOT MANY BALLASTS HAVE FAILED UNTIL RECENTLY AND SINCE THEY ARE UNATTAINABLE, IT HAS BEEN NECESSARY TO TAKE 840HZ BAL-LASTS OUT OF HALLWAY FIXTURES, REPLACING THESE WITH 60HZ BALLASTS AND BRINGING 60HZ POWER TO THE HALLWAY. THIS INSTALLATION HAS HAD NO AUDIBLE NOISE PROBLEM ACCORDING TO THE BUILDING SUPERINTENDENT.

**SEMICONDUCTOR ELECTRONIC H.F. GENERATORS**

**Power Transistor Inverters and Converters**

Soon after the announcement of power transistors, capable of a fast switching function, work began to develop inverters to produce high frequency power for operation of fluorescent lamps.

28 In 1958 the General Electric Lamp Division developed a fluorescent system for bus lighting using some of the first available power transistors. The resulting central inverter operated 16, 42" T-6 slimline lamps at 3000Hz from the 12 volt bus battery at a power efficiency of 88%. (Figs. 19, 20).

24 At about the same time, Westinghouse announced development of a power transistor multi-lamp frequency converter for operation on conventional 60Hz lines. Due to the low voltage rating of available transistors, several were connected in series to
PERFORM THE SWITCHING FUNCTION. OUTPUT FREQUENCY WAS 1500Hz AND SPECIAL LEAD LAG BALLASTS WERE DESIGNED TO OPERATE 40 WATT RAPID START LAMPS. POWER CONVERSION EFFICIENCY WAS SAID TO BE APPROXIMATELY 94%. (FIGURE 21). A MULTI-KILOWATT PROTOTYPE INSTALLATION WAS SUBSEQUENTLY MADE IN A HAMILTON ONTARIO BUILDING. ONE OF THE DIFFICULTIES WITH SERIES CONNECTED POWER TRANSISTORS IS THE CASCADE FAILURE OF TRANSISTORS WHERE AN UNUSUALLY HIGH VOLTAGE TRANSIENT APPEARS ACROSS THE GROUP. APPARENTLY THIS WAS ONE OF THE PROBLEMS IN THIS EARLY INSTALLATION.

One of the first applications for power transistors in fluorescent lighting was for operation of fluorescent lamps in hand lanterns, transportation emergency and portable lighting. (FIGURE 22). The basic circuit uses only one transistor and a correspondingly low component count. Approximately one million units of various types have been made and are currently in use. The reliability of this circuit was recognized when it was chosen to operate special high current fluorescent lamps in the Sky Lab.

**Silicon Controlled Rectifier 3000Hz Frequency Converter**

The General Electric Co. announced the Silicon Controlled Rectifier soon after the power transistor was made available. The S.C.R. provided the needed characteristics for switching large blocks of power which the early power transistors did not have. The principal advantages were high voltage and high current ratings.
Motor generator sets producing frequencies in the 420 to 840 Hz range had established a great deal of interest in central supplies for operating fluorescent lamps as the foregoing applications indicated. However, the maximum power efficiency attainable with MG sets was about 80% so the gain over conventional systems was accounted for by reduction in ballast losses coupled with the increase in lamp efficacy.

It was soon discovered that S.C.R.'s could be applied in switching circuits to provide power up to 3000 Hz. The General Electric Co. then initiated development work to build frequency converters at power efficiencies of 90% to replace the lower frequency, lower efficiency motor generator sets for an improvement in lighting economics. A higher frequency than 3000 Hz was preferred from the standpoint of lamp efficacy, but the S.C.R.'s at that time would require de-rating to accomplish the same power output at the faster switching speed and this was not economically feasible.

The first converters were installed in various General Electric Co. facilities for trial and several changes were made in circuits and components before the first 20 K.W. converter was designed for the market. (Figure 23). It was recommended that the frequency converter be located in a wiring closet adjacent to the wiring area or in the core area of the building so heat losses are outside the air conditioned area. In this way, full advantage can be taken of the greatly reduced losses of the 3000 Hz ballasts located in the lighted and air conditioned area.
It was decided to design the system for commercial lighting applications using the popular high production 40 watt rapid start fluorescent lamp. A four-lamp series sequence capacitor ballast including a preheat transformer was designed for the 3000Hz system (Fig. 24). Percent lumens per watt of the fixture and the overall system efficiency vs. frequency are shown in Fig. 25. 60Hz wiring can be used without de-rating for 3000Hz as shown in Fig. 26. It will be noted that most voltage changes are positive due to effects of the leading power factor load and the inductive reactance of the line. Voltage calculations were based on a simplified equivalent circuit with all of the lamp load concentrated at the end of the circuit. Normally, distribution of lamps and ballasts on branch circuits means that voltage changes will be less than listed in the table. A composite schematic (Fig. 27) shows the system components. A preliminary economic comparison is shown in the Table of Fig. 28. Subsequent economic comparisons showed time required to recover additional investment from 1½ to 3½ years depending on size of installation and power rates. Gain in system efficacy in lumens per watt over 60Hz including the frequency converter losses is 16%.

Applications

In order to determine what the experience had been with the 3000Hz systems, two installations were visited in 1978 and inquiries were made by telephone for information on two others. Three of the four installations were still operating at the time.
THE UNIVERSITY OF NEW MEXICO
LIBRARY BUILDING

THIS WAS THE FIRST INSTALLATION OF 3000Hz. THE INSTALLATION INVOLVED A TOTAL OF OVER 200 K.W. OF FLUORESCENT LIGHTING SUPPLIED BY FOURTEEN 20 K.W. FREQUENCY CONVERTERS. LIGHTING FIXTURES CONTAINED 3000Hz FOUR-LAMP BALLASTS OPERATING THE CONVENTIONAL 40 WATT RAPID START FLUORESCENT LAMPS.

TWO COMPANIES PROVIDED THE SPECIAL FOUR-LAMP 40 WATT RAPID START BALLASTS EACH IN THE SAME TYPE OF FIXTURE, BUT ON DIFFERENT FLOORS. ONE MANUFACTURER'S BALLASTS WERE NOISY DUE TO A DIFFERENCE IN THE PREHEAT TRANSFORMERS DESIGN. CORRECTION WAS MADE BY PADDING THE BALLASTS. SOME DIFFICULTY WAS EXPERIENCED INITIALLY WITH FREQUENCY CONVERTERS DUE TO THE CONFINED SPACE IN WHICH EACH WAS LOCATED RESULTING IN OVERHEATING. THIS PROBLEM WAS SOLVED BY PROPER VENTING OF THE COMPARTMENTS.

WITH THE INITIAL PROBLEMS CLEARED UP, THE INSTALLATION OPERATED PROPERLY BUT WITH OCCASIONAL MAINTENANCE INVOLVING FREQUENCY CONVERTER COMPONENTS.

EXPERIENCE

IN THE PAST FEW YEARS, MAINTENANCE OF THE 3000Hz FREQUENCY CONVERTERS HAS BEEN COSTLY DUE TO OBSOLETE COMPONENTS SUCH AS THE BALLASTS AND CERTAIN SPECIAL PARTS IN THE CONVERTERS. ALSO E.M.I. IN THE FORM OF LINE CONDUCTION BECAME A PROBLEM IN THE LIBRARY WHEN A RECENTLY INSTALLED ELECTRONIC BOOK THEFT DETECTION SYSTEM MALFUNCTIONED PERIODICALLY DUE TO LINE NOISE.
The 3000Hz installation was replaced by conventional 60Hz fluorescent lighting in October 1978 after 14 years of operation.

The O'Neida County Office Building, Utica, N.Y.

In 1968, a new 10 floor office building was equipped with 15, 40 k.W. frequency converters providing approximately 560 k.W. of 3000Hz lighting. Hallways were lighted with a conventional 60Hz rapid start system.

Audible noise from lighting fixtures in a large conference room was one of the initial problems. This was subsequently corrected by re-mounting and padding the ballasts. A visit to this installation in September 1978, revealed several problems, one of which involved the failure of some lamps to start or slow starting in the morning when ambient temperatures were somewhat lower than normal. The starting difficulties were due ostensibly to excessive spacing between the lamps and the grounded metal of the fixture and possibly low line voltage at times in this area of the building. On my tour of the building, some audible noise was apparent in an isolated area on two of the floors, but the highest level of noise was produced by a 60Hz fixture in the hallway on one floor.

In a conference with the Manager of Building Maintenance, I learned that there had been approximately 100 ballast failures out of a total of 3700 in the building for the first 10 years of operation. Since this is only 2%, the concern was not in the number of failures. However, the ballasts had become difficult
TO OBTAIN AND THE COST MANY TIMES HIGHER THAN THE ORIGINAL UNITS.
THE FREQUENCY CONVERTERS HAVE A RELATIVELY COMPLEX CIRCUIT AND
GENERALLY REQUIRE SERVICE FROM HIGHLY SPECIALIZED PERSONNEL.
HOWEVER, IN THIS BUILDING, THE MANAGER OF BUILDING MAINTENANCE
IS UNUSUALLY WELL QUALIFIED TO PERFORM ALL THE NEEDED REPAIRS.

THE COST OF REPLACEMENT PARTS HAS INCREASED SHARPLY SINCE
THE 3000Hz SYSTEM WAS TAKEN OFF THE MARKET AND FOR THIS REASON
THE INSTALLATION MAY BE REPLACED IN THE NEAR FUTURE. 43 NO EX-
TENSIVE TESTS HAVE BEEN MADE IN THIS BUILDING TO DETERMINE THE
OVERALL COMPARATIVE ECONOMY OF THE SYSTEM, BUT IT IS ASSUMED
THAT ENERGY SAVINGS CORRESPOND WITH THE PUBLISHED INFORMATION
OR APPROXIMATELY 16%.

BROWN JUNIOR HIGH SCHOOL
MCALENN, TEXAS

THIS INSTALLATION PLACED IN SERVICE IN 1967, CONSISTED OF
7 - 20 K.W. 3000Hz FREQUENCY CONVERTERS PROVIDING ABOUT 120 K.W.
OF LIGHTING FOR CLASSROOMS, AUDITORIUM AND OFFICES. INITIAL
PROBLEMS CENTERED ON MARGINAL STARTING OF LAMPS IN THE AUDITORIUM,
PRESUMABLY BECAUSE THE SPACING BETWEEN THE LAMP AND THE GROUNDED
METAL OF THE FIXTURE WAS TOO GREAT TO PROVIDE THE PROPER STARTING
AID. THIS WAS LARGELY CORRECTED BY USING METAL LOUVERS TO NARROW
THE GAP, BUT SLOW STARTING WAS SOMETIMES ENCOUNTERED WHEN AMBIENT
TEMPERATURES IN THE MORNING WERE LOW AND THIS CONDITION WAS THOUGHT
TO BE DUE TO MARGINAL STARTING VOLTAGE.

THE ARCHITECT SAID THAT AS THE SYSTEM AGED, THERE WERE SOME
PROBLEMS WITH MAINTENANCE OF THE FREQUENCY CONVERTERS, BECAUSE
OF PERSONNEL WHO WERE NOT TECHNICALLY QUALIFIED TO MAKE REPAIRS OR ADJUSTMENTS. A CENTRAL SERVICE COMPANY WAS CALLED UPON WHEN NEEDED, BUT AS THE SERVICE COST INCREASED DUE TO OBSOLETE SYSTEM COMPONENTS, IT WAS DECIDED TO REPLACE THE 3000Hz LIGHTING AFTER 10 YEARS OF SERVICE.

THE OHIO POWER CO.
CAMBRIDGE, OHIO

THE OHIO POWER COMPANY, AN ELECTRIC UTILITY KNOWN FOR ITS INNOVATIVE PROGRAMS, DECided TO EQUIP A NEW OFFICE BUILDING IN CAMBRIDGE, OHIO WITH THE NEW 3000Hz LIGHTING SYSTEM.

A VISIT BY THE WRITER TO THIS FACILITY IN OCTOBER, 1978, RESULTED IN THE FOLLOWING INFORMATION: THE BUILDING WAS EQUIPPED WITH TWO GENERAL ELECTRIC 20 K.W. SILICON CONTROLLED RECTIFIER FREQUENCY CONVERTERS. THE LOBBY AND MEETING ROOM ARE COMFORTABLY LIGHTED WITH A MASSIVE LUMINOUS CEILING WHICH PROVIDED A MAXIMUM OF 400 FOOTCANDLES OF ILLUMINATION. AN ACRYLIC LENS IN SQUARES AND SMALL CELL CROSS HATCH LOUVERS PREVENT GLARE. THE ILLUMINATION LEVEL COULD BE LOWERED BY SWITCHING ROWS OF LAMPS. BORDER LAMPS TO LIGHT THE WALLS ARE POWERED BY CONVENTIONAL 60Hz ALONG WITH INCANDESCENT SPOTS AND FLOODS TO COMPLETE THE LIGHTING DEMONSTRATION AREA. LIGHTING IN THE GENERAL AND PRIVATE OFFICES USE TWO, THREE AND FOUR LAMP FIXTURES WITH 3000Hz BALLASTS MADE BY ALADDIN ELECTRONICS.

THE TWO FREQUENCY CONVERTERS ARE LOCATED IN THE CONTROL ROOM AT THE CENTER OF THE BUILDING. A VENT TO THE OUTSIDE WITH A BLOWER AND EXHAUST FAN PROVIDES SUFFICIENT AIR CIRCULATION TO REMOVE THE HEAT CAUSED BY CONVERTER LOSSES WHICH AMOUNT TO ABOUT
8 to 10% depending on load according to tests made by the manufacturer.

In a tour of the building, no audible noise was apparent from the 3000Hz lighting even in low level ambient locations. A combination battery - AC portable transistor A.M. radio was operated in the building in various locations without interference. When plugged into an office 60Hz outlet, conducted noise could be detected, but a strong signal would override the noise.

The professional way in which this rather complex high frequency lighting system was installed was quite impressive. Although Ohio Power maintained the lighting system by making their own adjustments and minor replacements, a contract with a Service Company was necessary to replace some of the parts in the frequency converters. Due to the obsolete components including ballasts, the cost of this service was intolerably high and the system was replaced in November, 1978 after 11 years of operation.

**High Frequency System Modernization**

**Magnetic Frequency Multipliers**

The basic purpose of the 360Hz frequency converter was to exploit the known advantages of high frequency operation of fluorescent lamps and to provide a system, capable of increasing lighting levels by increasing lamp efficacy, lamp loading and reducing ballast losses. Additional advantages were obtained, such as elimination of strob. effect, use of capacitor ballasts and regulation of
LUMEN OUTPUT FOR POWER MANAGEMENT. THE FORMER ADVANTAGES ARE
HIGHLY DESIRABLE AND THE LATTER IS SOUGHT AFTER TODAY IN ENERGY
EFFICIENT SYSTEMS. AT THE TIME, THIS FIRST USE OF A TRANSFORMER-
LIKE FREQUENCY CONVERTER FOR FLUORESCENT LIGHTING, APPEARED TO BE
ECONOMICALLY FEASIBLE IN SIZES OF 25 AND 40 K.W. FOR COMMERCIAL
AND INDUSTRIAL LIGHTING. ALTHOUGH RELIABLE, IT WAS FOUND TO BE
NON-COMPETITIVE IN INITIAL COST WITH THE NEW 40 WATT RAPID START
CONVENTIONAL 60HZ LIGHTING WHICH WAS THEN THE OPTIMUM CONVENTIONAL
SYSTEM. MAGNETIC FREQUENCY MULTIPLIERS WERE THEN CONFINED TO
SPECIAL APPLICATIONS SUCH AS THE EXPERIMENTAL PLANT GROWTH PRE-
VIOUSLY DESCRIBED.

ANY UPDATING OF THE DEVICE UTILIZING THE MAGNETIC FREQUENCY
MULTIPLIER CONCEPT, WOULD NO DOUBT INVOLVE NEW IMPROVED MAGNETIC
MATERIALS AND CONVERSION OF 60HZ TO A MUCH HIGHER HARMONIC FOR
SMALLER AND MORE EFFICIENT COMPONENTS.

THE MOTOR GENERATOR

THIS SYSTEM PROVIDING POWER AT 420 OR 480HZ, WAS SELECTED FOR
ITS AVAILABILITY, RELATIVELY LOW COST PER K.W. IN SIZES OF 20 TO
100 K.W., AND RELIABILITY IN OPERATION. APPLICATIONS WERE LIMITED
TO LARGE INDUSTRIAL OR COMMERCIAL INSTALLATIONS WHERE THE SPECIAL
ADVANTAGES OF HIGH FREQUENCY OPERATION WERE NEEDED OR WHERE OPERA-
TING EFFICIENCY AND CORRESPONDING ECONOMICS WERE FAVORABLE WHEN
COMPARED TO 60HZ. THE HIGH DISTRIBUTION VOLTAGE, 600/300 PRO-
VIDED BOTH STARTING AND OPERATING VOLTAGE FOR SLIMLINE INSTANT
START LAMPS FROM 48" T-12 TO 96" T-12 SIZES. THE SMALL CAPACITOR
BALLAST MADE IT POSSIBLE TO OPERATE THE LAMPS AT ANY WATTAGE WITH-
IN LAMP RATINGS BY SELECTION OF THE CORRESPONDING CAPACITOR SIZE
IN MICROFARADS.

IMPROVEMENT OF THE 420 & 840HZ MOTOR-GENERATOR SYSTEM FROM THE STANDPOINT OF OVERALL EFFICIENCY WOULD BE DIFFICULT WITHOUT INCREASING THE GENERATOR FREQUENCY TO LEVELS ABOVE 10KHz, WHERE GAINS IN LAMP EFFICACY ARE SIGNIFICANT. HOWEVER, THE GENERATOR INTERNAL LOSSES AT THE HIGHER FREQUENCY WILL INCREASE AND TEND TO REDUCE OR CANCEL THE GAINS IN LAMP EFFICACY. ALSO THE COST OF SPECIAL WIRING AND SWITCHGEAR, NEEDED TO AVOID EXCESSIVE LOSSES IN THE DISTRIBUTION SYSTEM, WOULD REDUCE THE ECONOMIC ADVANTAGE OF THE SYSTEM.

TOTAL ENERGY GAS TURBINE
HIGH FREQUENCY LIGHTING SYSTEM

THE SYSTEM AS DESCRIBED PREVIOUSLY AT THE NORTHERN ILLINOIS GAS FACILITY IS VIABLE TODAY WITH DISTRIBUTION OF 420Hz POWER FOR LIGHTING. THE OVERALL EFFICIENCY OF LIGHTING IS DIFFICULT TO OBTAIN BECAUSE THE ENERGY EXPENDED IN THE TURBINE PROVIDES USEFUL HEAT AND AIR CONDITIONING AS WELL AS ELECTRIC POWER. HOWEVER, THE VOLTAGE FOR DISTRIBUTION IS OBTAINED DIRECTLY FROM THE COILS OF THE GENERATOR SO NO INTERMEDIATE TRANSFORMER IS REQUIRED. SINCE CAPACITOR BALLASTS ARE USED THROUGHOUT, ONLY THE POWER FACTOR CORRECTION INDUCTIVE REACTORS AT EACH BRANCH CIRCUIT HAVE A SIGNIFICANT LOSS. (APPROXIMATELY 2 WATTS PER LAMP.) AN ALTERNATE SYSTEM FOR MAXIMUM ECONOMY, USES A LOW POWER FACTOR GENERATOR CAPABLE OF VOLTAGE REGULATION WITH A CAPACITIVE LOAD.

IN AN ARTICLE WHICH APPEARED IN THE PLANT ENGINEERING NOVEMBER 16, 1972, A.G. WARD, WHO HELPED DESIGN THE NORTHERN
ILLINOIS GAS 420Hz LIGHTING SYSTEM CONCLUDED AS FOLLOWS:

"SOME OF THE ECONOMICS RESULTING FROM HIGH-FREQUENCY USE MAY BEST BE ILLUSTRATED BY AN EXAMPLE OF THE SAVINGS FOUND IN A TYPICAL LIGHTING INSTALLATION COVERING 120,000 SQUARE FEET WITH INTENSITY OF 120 FOOT CANDLES USING 1' X 4' FIXTURES":

AIR CONDITIONING 28 TONS
POWER SOURCE & WIRING SAVING 100 K.W.
ROOF LOADING 16 TONS

69-71 FROM REPORTS MADE OF PERFORMANCE CHARACTERISTICS OF TOTAL GAS TURBINE SYSTEMS, STILL IN USE, IT WOULD APPEAR THAT 420Hz FLUORESCENT LIGHTING IS SATISFACTORY AND PROVIDES A SUFFICIENT GAIN OVER 60Hz IN BOTH INITIAL AND OPERATING COST TO MAKE IT AN ENERGY EFFICIENT CENTRAL HIGH FREQUENCY SYSTEM. 69 POWER AT 420Hz IS ALSO BEING USED TO OPERATE MERCURY LAMPS AND MAY BE APPLIED TO 49 METAL HALIDE AND HIGH PRESSURE SODIUM LAMPS AS WELL.

S.C.R. 3000Hz FREQUENCY CONVERTER

LARGE CENTRALLY LOCATED FREQUENCY CONVERTERS OF COMPLEX DESIGN, ENGENDERED A NUMBER OF PROBLEMS, SOME OF WHICH WERE NOT UNDER CONTROL OF THE CONVERTER MANUFACTURER. THE PREVIOUSLY DESCRIBED EXPERIENCES GAVE STRONG EVIDENCE THAT A COMPLETE SYSTEM APPROACH OR A COMPLETELY ENGINEERED PACKAGE WOULD BE NEEDED TO INSURE PROPER OPERATION AND AVOID SUBSEQUENT REVISION. SPECIFI-
CATIONS, NECESSARILY INCLUDED COMPONENTS SUCH AS BALLASTS, FIX-
TURES, WIRING, CONDUIT, SWITCHGEAR, FREQUENCY CONVERTER, CON-
VERTER LOCATION AND MAXIMUM AMBIENT TEMPERATURES. IF ANY ONE OF
THE SPECIFICATIONS WAS NOT FOLLOWED, RESULTS COULD BE AUDIBLE
NOISE, MARGINAL STARTING OF LAMPS, OR PREMATURE BALLAST FAILURES.
DUE TO THE NEWNESS AND COMPLEXITY OF THE FREQUENCY CONVERTER,
QUALIFIED PERSONNEL TO ADJUST AND MAKE MINOR REPAIRS WERE USUALLY
NOT AVAILABLE AT THE LIGHTING INSTALLATION AND QUALIFIED SERVICE
COMPANIES WERE FEW AND FAR BETWEEN. WESTINGHOUSE SUBSEQUENTLY
DEVELOPED A FREQUENCY CONVERTER USING S.C.R.'S, AND HAVE REPORTED
SIMILAR PROBLEMS OF AUDIBLE NOISE AND CONVERTER MAINTENANCE IN
A LARGE COMMERCIAL LIGHTING APPLICATION.

THE ELECTRONIC SILICON CONTROLLED RECTIFIER, CENTRALLY LOCATED
3000Hz FREQUENCY CONVERTER IS AN ENERGY EFFICIENT SYSTEM IN 20
AND 40KW SIZES. HOWEVER, PROBLEMS EXPERIENCED SUCH AS AUDIBLE
NOISE AND FREQUENT MAINTENANCE, WILL HAVE TO BE SOLVED TO MAKE
IT AN ACCEPTABLE AND COST EFFECTIVE SYSTEM.

MODULAR, BRANCH CIRCUIT HIGH FREQUENCY SYSTEMS
(A CONCEPT FOR AN IMPROVED ENERGY EFFICIENT SYSTEM)

A CONCEIVABLE SYSTEM TO OVERCOME SOME OF THE DISADVANTAGES
OF M-G SET AND S.C.R. CENTRALLY LOCATED FREQUENCY CONVERTERS IS
A BRANCH CIRCUIT CONVERTER LOCATED AT OR NEAR THE WIRING PANELS
ON EACH FLOOR OF THE BUILDING OR IN A VENTILATED WALL OR CEILING
CABINET FOR 'LOAD CENTER' DISTRIBUTION OF HIGH FREQUENCY POWER.
FIG. 29 IS A BLOCK DIAGRAM ILLUSTRATING A CONCEPT IN WHICH D.C.
POWER IS DISTRIBUTED TO EACH OF THE BRANCH CIRCUIT OR 'LOAD
center inverters. Three-phase 60Hz A.C. power is distributed through risers with normal wiring to each floor and rectified in one block. The D.C. power is then distributed to each inverter through the switch panel at a voltage and current within the Electric Code limits for D.C. distribution.

Power Management providing changes in illumination with a corresponding change of input power can be obtained by at least two methods. Control of the D.C. input to each inverter by adjusting the A.C. input to the control rectifier, or by changing the output frequency of each individual inverter with a single control at the switch panel. Either method could provide pre-determined steps, continuous manual dimming over a range or automatic control by adjustable timer or photocells.

Inverter output frequency can be varied by adjusting the oscillator driving frequency for various switching speeds. If capacitor ballasts are used, the lumen output will vary on a nearly linear curve with frequency, providing output voltage of the inverter is held constant.

System efficiency will increase at the lower illumination level due to the reduced lamp watts. The variable frequency system would apply in the form shown in Fig. 29, only to the instant start lamp arrangement. Minimum and maximum lamp current would be limited to that specified by the Lamp Manufacturer for any lamp shown. In the case of the instant start or Slimline lamps, the practical range of light output would be a ratio of
ABOUT 3 TO 1.

Branch circuit inverters of approximately 5kW, with 'load center' distribution will provide the following advantages:

1. Short high frequency distribution lines
2. Distribution of frequencies above the human hearing range (25kHz-50kHz)
3. Silent operation
4. Maximum lamp and ballast efficacy
5. Simplified power management with frequency control of light levels
6. Reduced ballast losses and lower fixture and lamp bulb wall temperatures
7. Lowest system operating cost
8. Variable design center lamp watts without use of premium low wattage lamps (choice of capacitor size)

One disadvantage that the branch circuit frequency converter shares with the large centrally located converters is the somewhat higher cost of switching small increments of lighting. This would not be a problem in a large unpartitioned area such as a general office. However, to obtain control of the lighting in small offices or rooms, wall switches electrically isolated from the main output of the inverter could operate a relay located in the ceiling.

STATE OF THE ART

Considerable progress has been made in semiconductor device and associated circuit technology, since the introduction of
ELECTRONIC FREQUENCY CONVERTERS. For example, the silicon control-LED rectifiers used in the General Electric frequency converters were limited in switching speed to 3000Hz without serious de-rating. Thyristors are now available with switching capabilities to 10KHz and are in use for inductive heating in sizes of 20kW and greater.

The power transistor has greatly improved characteristics in current and voltage, permitting design of inverters to at least 10kW with output frequencies of 25KHz and above. Some manufacturers have designed and marketed frequency converters of this type for special applications and could no doubt meet the requirements of the aforementioned branch circuit inverter for fluorescent lighting. A discussion with one manufacturer indicates that power transistor inverters of 5, 10 and 15kW capacity would have power efficiencies of 92, 93 and 95% respectively.

In addition to higher power efficiency, the multi-lamp branch circuit frequency converters would be expected to have a lower cost per kW than individual two-lamp electronic ballasts each of which must have its own inverter.

An estimate using presently available standard 60Hz lamps and ballasts as a base and 28 previously published percentage increases in lamp efficacy at high frequencies, provides the following comparison; at an output frequency of 25KHz, utilizing capacitor ballasts and a 5kW frequency converter with a power efficiency of 92%, the gain in system lumens per input watt over
60Hz is approximately 34% for equal light output and 27% for equal lamp watts. The latter choice would provide higher lumen output with fewer fixtures required for a given illumination level.

In 1978, low loss, higher efficiency 2-lamp 40 watt rapid start 60Hz ballasts became available. If this ballast becomes the base for comparison with the 25KHz system, the net gain is considerably lower, 20% for equal light output and 16% for equal lamp watts. A study by a subcommittee of the American National Standards Institute is underway to update the published data of 1960 on high frequency lamp characteristics. It is not known at this date when this information will be available. The preceding figures do not include the increases in fixture efficacy resulting from reduced ballast losses and correspondingly lower lamp bulb wall temperatures. The additional gain for this feature in favor of the 25KHz branch circuit system is thought to be at least 6%.

In addition to the fluorescent lamp, it is also advantageous to operate Mercury, Metal Halide and High Pressure Sodium Lamps on high frequency power. At some frequencies, the simple low cost capacitor has been used as a ballast for Mercury lamps.

SYSTEMS ECONOMICS

D.C. DISTRIBUTION

Referring to Fig. 29, the D.C. distribution system can be quite simple from the standpoint of the rectifier, provided the

THE ONLY PURPOSE IN THE D.C. DISTRIBUTION SYSTEM AS AN INPUT TO THE INVERTERS, VS. A.C. INPUT TO FREQUENCY CONVERTERS WOULD BE IN THE ECONOMY. EITHER TYPE OF HIGH FREQUENCY SUPPLY WOULD SERVE THE SAME FUNCTION AS A BRANCH CIRCUIT INVERTER WITH A D.C. INPUT OR A FREQUENCY CONVERTER WITH AN A.C. INPUT. ONE MANUFACTURER OF FREQUENCY CONVERTERS AND INVERTERS, ESTIMATES A COST OF $36/KW FOR THE D.C. SECTION OF A 5KW FREQUENCY CONVERTER.

**Comparative System Economics**

IN ORDER TO ILLUSTRATE THE POTENTIAL SAVINGS IN ENERGY AND COST OF THE LOAD CENTER HIGH FREQUENCY SYSTEM, CERTAIN KNOWN VALUES OF SOME CHARACTERISTICS WERE COMBINED WITH ESTIMATES BASED ON EXPERIENCE TO CALCULATE THE FOLLOWING:
1. THE GAIN IN OVERALL EFFICIENCY OF THE HIGH FREQUENCY SYSTEM OVER THE 60Hz CONVENTIONAL LAMP AND BALLAST, OPERATING IN OPEN AND ENCLOSED FIXTURES.

2. THE SAVING IN WATTS, REPRESENTED BY THIS GAIN ON A PER KILOWATT BASIS.

3. CALCULATION OF THE DOLLAR SAVING PER YEAR PER KW AT VARIOUS RATES PER KW HR.

4. APPLICATION OF DOLLAR SAVINGS FOR A TWO YEAR PAYBACK TO DETERMINE THE ACCEPTABLE COST PER KW FOR THE HIGH FREQUENCY INVERTER AND ASSOCIATED COMPONENTS.

5. CALCULATION OF THE NUMBER OF YEARS TO PAY OFF THE HIGH FREQUENCY COMPONENTS AT AN ESTIMATED INVERTER AND D.C. SYSTEM COST.

The lumen output of 2-40WATT lamps with a 60Hz magnetic ballast is: 6300 x .95 = 5985. Using the standard ballast input of 96 watts, and the high efficiency ballast input of 85 watts, we have the following:

Standard Ballast System Efficacy = \[
\frac{5985}{96} = 62.3 \text{ L.P.W.}
\]

High Efficiency Premium Ballast System Efficacy = \[
\frac{5985}{85} = 70.4 \text{ L.P.W.}
\]

At 25KHz, the 40 watt rapid start lamp gains approximately 12% in efficacy while operating the lamp at rated watts.

Lumens = 6300 x 1.12 = 7056

L.P.W. = \[
\frac{7056}{80} = 88.2 \text{ LAMP L.P.W.}
\]

Estimated increase in lamp efficacy due to operation at lower lamp watts to produce equal lumen output of 5985 = 5%

Lamp L.P.W. = 88.2 x 1.05 = 92.6

Lamp Watts = \[
\frac{5985}{92.6} = 64.6
\]

*Minimum percentage of rated lumen output is 95% with lamps operating at less than rated watts.
ESTIMATED CONVERTER POWER EFFICIENCY 92%

System Watts = $\frac{64.6}{.92} = 70.2$

Instant Start System L.P.W. = $\frac{5985}{70.2} = 85.3$

Estimated Rapid Start Preheat Transformer Loss

1.5 Watts

Rapid Start System L.P.W. = $\frac{5985}{71.7} = 83.4$

Table I shows the saving in watts per KW comparing each high frequency system, Rapid Start and Instant Start with the two 60Hz magnetic ballast systems. (Page 48)

The two converter cost estimates include the cost of the inverter and the D.C. distribution system, but the range in cost per KW is shown for 5KW and 10KW inverter sizes. The cost estimates are made from figures available on a similar power transistor inverter now being made, but with the higher production quantities, needed for lighting systems. No claim is made for the accuracy of these figures.

While the comparisons in Table I are self-explanatory, it should be pointed out that the 25KHz rapid start system uses the same 40 watt lamp as the 60Hz systems and indirect costs such as maintenance, lamp life and replacement costs will be the same. However, the instant start lamps such as the 40W T-12 and the 48" T-12 slimline lamps are produced in lower quantities and are higher in cost. Also the lamp life for 60Hz operation is considerably less. If the experience with lamp life as related at the Northern Illinois Gas Co. in their 420Hz operation can be equated to 25KHz operation, the life of these lamps will be about equal to the rapid start lamps. This can be determined only by
DEMONSTRATION SHOWING PERFORMANCE OF THE INSTANT START LAMPS IN AN ACTUAL INSTALLATION OR BY OFFICIAL LIFE TESTS OF THE LAMP MANUFACTURERS.

THE EFFICIENCY FIGURES AND THE DOLLAR SAVINGS SHOWN IN TABLE I MAY BE CONSERVATIVE SINCE NO CREDIT IS GIVEN FOR THE REDUCED WATTAGE AND CORRESPONDING LOWER TEMPERATURE OF AN ENCLOSED FIXTURE. ESTIMATES FROM PREVIOUS TESTS INDICATE AN ADDITIONAL NET GAIN OF AT LEAST 6% DUE TO THE REDUCED LAMP BULB WALL TEMPERATURES. A MULTIPLYING FACTOR OF 1.06 IN WATTS AND DOLLARS SAVED CAN BE APPLIED TO THE TABLE FOR ESTIMATES, WHEN THE ENCLOSED FIXTURES ARE OPERATED IN NORMAL ROOM AMBIENT TEMPERATURES.

SYSTEM COMPONENTS

IN ADDITION TO THE FREQUENCY CONVERTER, OTHER COMPONENTS TO BE CONSIDERED IN THE DEVELOPMENT AND DESIGN OF AN OPTIMUM ENERGY EFFICIENT SYSTEM ARE: THE LAMP, BALLAST, LIGHTING FIXTURE, WIRING, CONDUIT AND SWITCHGEAR.

THE FLUORESCENT LAMP

AT THE PRESENT WRITING, THE STANDARD LAMP DESIGNED FOR OPERATION ON CONVENTIONAL 60Hz CIRCUITS IS THE ONLY LAMP AVAILABLE FOR HIGH FREQUENCY SYSTEMS. WITH ONE EXCEPTION, ALL ELECTRICAL CHARACTERISTICS CHANGE WITH RISING FREQUENCY. THE EXCEPTION IS THE SPECIFIED VOLTAGE FOR PREHEATING THE CATHODES OF RAPID START LAMPS. SINCE RESISTANCE IS THE ONLY LOAD, A CHANGE IN FREQUENCY WILL NOT ALTER THE HEATING OF THE CATHODE. BOTH STATIC AND
TABLE I
SYSTEM COMPARISON ENERGY SAVING AND TIME TO PAY OFF ADDITIONAL INVESTMENT IN HIGH FREQUENCY CONVERTER (BASED ON ENCLOSED, (WRAP AROUND) FIXTURES) (4000 HOURS PER YEAR OPERATION)

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>EFF.</th>
<th>PERCENT</th>
<th>CONVERTER</th>
<th>PAY BACK</th>
<th>WATTS</th>
<th>KW HRS.</th>
<th>DOLLARS SAVED/YR/KW</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td></td>
<td></td>
<td>Magnetic Ballast</td>
<td>62.3</td>
<td>--</td>
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<td></td>
<td></td>
<td></td>
<td>Standard Lamp</td>
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<tr>
<td>(2)</td>
<td></td>
<td></td>
<td>High Efficiency</td>
<td>70.3</td>
<td>13%</td>
<td>130</td>
<td>520</td>
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<td></td>
<td>Magnetic Ballast</td>
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<td></td>
<td>Standard Lamp</td>
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<tr>
<td>(3) 25Khz</td>
<td>3/1</td>
<td>83.4</td>
<td>Rapid Start</td>
<td>340</td>
<td>1360</td>
<td>40.80</td>
<td>68.00</td>
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<td></td>
<td></td>
<td></td>
<td>Converter</td>
<td></td>
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<td></td>
<td>Cost 2Yr P.B.</td>
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<td></td>
<td></td>
<td></td>
<td>@$300/K.W.</td>
<td>Yrs. to P.B.</td>
<td>7.3</td>
<td>4.4</td>
<td>3.1</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>@$200/K.W.</td>
<td>Yrs. to P.B.</td>
<td>4.9</td>
<td>2.9</td>
<td>2.2</td>
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<td>Converter Cost</td>
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<td>Per K.W. 2Yr</td>
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<td></td>
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<td>P.B.</td>
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<td></td>
<td></td>
<td>@$300/K.W.</td>
<td>Yrs. to P.B.</td>
<td>13.9</td>
<td>8.3</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>@$200/K.W.</td>
<td>Yrs. to P.B.</td>
<td>9.2</td>
<td>5.6</td>
<td>4.0</td>
</tr>
<tr>
<td>(4) 25Khz</td>
<td>4/1</td>
<td>85.3</td>
<td>Instant Start</td>
<td>360</td>
<td>1440</td>
<td>43.20</td>
<td>72.00</td>
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<td>40W T-12</td>
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<td>Converter Cost</td>
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<td></td>
<td>Per K.W. 2Yr</td>
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<td>P.B.</td>
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<td></td>
<td></td>
<td>@$300/K.W.</td>
<td>Yrs. to P.B.</td>
<td>6.9</td>
<td>4.2</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>@$200/K.W.</td>
<td>Yrs. to P.B.</td>
<td>4.6</td>
<td>2.8</td>
<td>2.0</td>
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<td>4/2</td>
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<td>Per K.W. 2Yr</td>
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<td></td>
<td>@$300/K.W.</td>
<td>Yrs. to P.B.</td>
<td>12.5</td>
<td>7.5</td>
<td>5.6</td>
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<td></td>
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<td></td>
<td>@$200/K.W.</td>
<td>Yrs. to P.B.</td>
<td>8.3</td>
<td>5.0</td>
<td>3.6</td>
</tr>
</tbody>
</table>

*aBased on use of Listed Standard 40W T-12 Fluorescent Lamps

Note: See explanation of method of operation in Economic Section of Report. This table should not be detached from report. $200/KW estimated cost for 10KW size, $300/KW for 5KW size.
Dynamic characteristics change for the same watts delivered to
the lamp. These include lamp voltage, current, power factor,
end losses, positive column efficacy, flicker, starting voltage,
reignition voltage, current and voltage wave forms and E.M.I.

The major lamp advantage gained by high frequency opera-
tion is the increase in lamp efficacy. This is due largely to
the decrease in end losses and the increase in positive column
efficacy with rising frequency. Factors found to influence
each phenomenon are delineated in the paper "New Parameters
for High Frequency Lighting Systems" by John H. Campbell, Il-
luminating Engineering Vol. LV, No. 5 May 1960. A few of the
most important factors of influence are, filling gas mixture
and pressure, bulb diameter and length and current wave form.

From the preceding information and data likely gathered since
the 1960 work, the Lighting Industry should look forward to the
design of an optimum fluorescent lamp for high frequency operation.

Several modifications have been made in lamp filling gas
mixture and pressure along with cathode construction to improve
lamp operation at 60Hz. It has been reported to me that some
of the changes have resulted in somewhat reduced gains in lamp
efficacy when the modified lamps now on the market are operated
at high frequencies.

The need for updating the 1960 lamp characteristic data has
been recognized by the American National Standards Institute
and a Subcommittee has been appointed to obtain lamp characteristic
DATA OVER A WIDE FREQUENCY RANGE. IN ADDITION TO LAMP INFORMATION, THE DATA IS NEEDED TO PROVIDE SPECIFICATIONS FOR HIGH FREQUENCY BALLASTS. AT PRESENT, DESIGNERS OF ELECTRONIC BALLASTS OR SYSTEMS HAVE LITTLE TO DEPEND UPON EXCEPT PREVIOUS PUBLICATIONS.

THE LIFE OF FLUORESCENT LAMPS IS A SUBJECT OF INTEREST, BUT THE ONLY OFFICIAL PUBLISHED TESTS HAVE BEEN WITH LAMPS OPERATED ON CONVENTIONAL 60Hz IN THE U.S. OR 50Hz IN EUROPE, RUSSIA OR JAPAN. ACTUAL EXPERIENCE WITH HIGH FREQUENCY OPERATION IN VARIOUS APPLICATIONS HERE AND IN RUSSIA SHOW AN INCREASE IN LAMP LIFE COMPARED TO CONTROL TESTS AT THE CONVENTIONAL FREQUENCIES.

47A RATHER COMPREHENSIVE TEST AT THE NORTHERN ILLINOIS GAS CO. SHOWED INCREASES IN LAMP LIFE OF 50% TO 3 TIMES DEPENDING ON LAMP LOADING OF SLIMLINE LAMPS AT 420Hz.

36,40 HIGH FREQUENCY LIGHTING SYSTEMS ARE BEING APPLIED IN THE U.S.S.R. THE TWO REFERENCED REPORTS WRITTEN IN 1961 AND 63 BY RUSSIAN AUTHORS, SHOW A SYSTEM FREQUENCY OF 2500Hz. A PREDICTED INCREASE IN LAMP LIFE OVER THEIR CONVENTIONAL 50Hz OPERATION WAS 22% TO 36% BASED ON ACCELERATED TESTS. THE TWO MAIN REASONS GIVEN FOR SPECIFYING HIGH FREQUENCY ARE; ELIMINATION OF FLICKER AND STROBOSCOPIC EFFECT, INCREASED EFFICIENCY AND THE GAIN IN THE OVERALL ECONOMY COMPARED TO 50Hz OPERATION.

DURING STARTING AND SUBSEQUENT LAMP OPERATION, THERE ARE SEVERAL CHANGES IN THE DYNAMIC CHARACTERISTICS OF LAMPS OPERATED ON HIGH FREQUENCY POWER, TWO OF WHICH CAN RESULT IN LONGER LAMP
LIFE. FIRST, DUE TO THE RAPIDLY CHANGING POLARITY, THE HOT SPOT NEEDED TO PROVIDE CATHODE THERMAL EMISSION FOR THE MAIN ARC, FORMS MUCH FASTER, REDUCING THE TIME IN WHICH SPUTTERING OF THE ACTIVE MATERIAL TAKES PLACE. THE ADVANTAGE OF THIS ACTION FOR INCREASED LIFE APPLIES MORE TO LAMPS WITH CATHODES DESIGNED FOR INSTANT STARTING SUCH AS THE SLIMLINE TYPES. WHEN THE LAMP IS OPERATING AT 60Hz, THE ARC IS TURNED ON AND OFF 120 TIMES PER SECOND AND REIGNITION TAKES PLACE AT THE SAME SPEED. DUE TO THE ON-OFF CYCLE, THE ARC TENDS TO 'HUNT' ACROSS THE CATHODE AND THE 'HOT SPOT' CAN MOVE, CAUSING SOME DISSIPATION OF ACTIVE MATERIAL DURING OPERATION. SECOND, AT HIGH FREQUENCIES SUCH AS 25KHz, VERY LITTLE OR NO REIGNITION OR HUNTING OCCURS AND THE 'HOT SPOT' REMAINS FIXED UNTIL THE ACTIVE MATERIAL IS USED UP, THE TRANSITION TO NEW POSITIONS, TAKING PLACE SLOWLY AND WITHOUT SPUTTERING. THIS ADVANTAGE WILL APPLY TO BOTH INSTANT AND RAPID START LAMPS.

FLUORESCENT LAMPS OPERATING AT 60Hz, DEVELOP PARASITIC OSCILLATIONS DURING REIGNITION EACH HALF CYCLE. IN THE POSITIVE PART OF THE CYCLE, ANODE OSCILLATIONS CAN VARY OVER A WIDE FREQUENCY RANGE WITH MOST OF THE ENERGY IN A BAND OF 300KHz TO 1600KHz. THIS RADIO NOISE, GENERATED DIRECTLY BY THE LAMP, PRODUCES A RANDOM TYPE OF INTERFERENCE IN THE A.M. BAND WHICH IS RADIATED FROM THE LAMP WITH A LOW FIELD STRENGTH AND CONDUCTED THROUGH THE POWER LINES TO THE BUILDING TRANSFORMER. DIRECT RADIATION AND LINE RADIATION IS GENERALLY LIMITED TO A FEW FEET. CONDUCTED NOISE IS ATTENUATED BY THE LINE, SUPPRESSORS IN THE
Ballast or by means of filters placed at each fixture. Fortunately the high frequency voltages from various lamps in a group are not in phase and do not add up, so the noise reaching the radio antenna at any frequency comes from a single lamp, producing the most noise.

When lamps are operated on unmodulated high frequency power, there are no anode oscillations so the lamp itself does not produce radio noise (E.M.I.). However, the frequency converter oscillator may produce radio noise and the lamp acting as an antenna will radiate it. Inverters generally produce somewhat more conducted noise than the comparable 60Hz lamp systems and will require line filters in some applications. Accelerated starting tests to determine lamp and ballast performance can be a guide to assist in the design of a new system. However, a control test of a conventional ballast with known starting and lamp characteristics must be operated on the same on-off cycle for comparison. Tests of this type have been conducted to determine whether an experimental ballast produces any deleterious effect on the lamp during the starting sequence. Accelerated tests are not considered a substitute for long term life tests such as conducted by lamp manufacturers to test their products.

Ballasts

The evolution of fluorescent lamp starting methods and corresponding ballasts may be of interest to the designer of electronic ballasts and other high frequency systems. A brief
ACCOUNT OF THIS HISTORY APPEARS IN THE REFERENCED REPORT ON PAGES 3-6.

The rapid start lamp and ballast, developed shortly before World War II, was not used during the war because the lamp required the grounded metal reflector or channel of the fixture as a starting aid. Since fixtures were then being made with non-metallic materials to save critical metals, the rapid start system could not be used.

After the war, the rapid start lamp and ballast came on the market, eventually using the series sequence circuit which reduced copper and iron and increased ballast efficiency. The improvement over the starter preheat circuit was significant because the annoying flicker during starting and at the end of lamp life, was eliminated along with the costly starter replacement. Rapid start lamps and ballasts became the industry standard for the popular 40 watt lamp and because of its high production and cathode design, the lamp is significantly lower in cost than comparable 40 watt instant or 48" T-12 instant start slimline lamps.

During the early application of rapid starting there were instances where lamps did not start properly because of inadequate starting aid at the fixture. There were also cases of instant starting, accompanied by severe sputtering of the cathode before the preheat temperature was high enough for thermal emission. The reference, "Flashing Characteristics of Fluores-
CENT LAMPS, GIVES A VISUAL DEMONSTRATION OF THIS EFFECT WHICH CAN SERIOUSLY REDUCE THE LIFE OF RAPID START LAMPS.

LAMP, BALLAST AND FIXTURE MANUFACTURERS HAVE CONCENTRATED THEIR EFFORTS TO IMPROVE THE RAPID START SYSTEM, RESULTING IN SPECIFICATIONS WHICH CIRCUMVENT THE EARLIER PROBLEMS.

HIGH FREQUENCY RAPID START BALLASTS

ALTHOUGH THERE ARE NO SPECIFICATIONS AS YET FOR HIGH FREQUENCY RAPID START BALLASTS, IT IS KNOWN THAT FLUORESCENT LAMPS WILL INSTANT START AT LOWER VOLTAGE THAN WITH 60Hz OPERATION. THIS REDUCES THE STARTING VOLTAGE GAP BETWEEN A TRUE RAPID START AND A PARTIAL OR COMPLETE INSTANT START. ON SHORT LAMPS SUCH AS THE 4, 6 AND 8 WATT TYPES, THIS DIFFERENCE IS ONLY A FEW VOLTS AT 20KHz AND ABOVE.

A RAPID START BALLAST FOR THE 40 WATT LAMP CAN BE DESIGNED FOR PROPER OPERATION AT 25KHz, BUT CARE MUST BE TAKEN TO KEEP THE TRUE R.M.S. VOLTAGE BELOW THE INSTANT START LEVEL OVER THE FULL RANGE OF INPUT LINE VOLTAGE. A PEAK TRANSIENT VOLTAGE ABOUT DOUBLE THE R.M.S. CAN BE TOLERATED IF OF SHORT DURATION. SINCE THERE ARE NO SPECIFICATIONS FOR RAPID STARTING AT HIGH FREQUENCY, THE EXPERIMENTAL OR PROTOTYPE BALLAST CAN BE CHECKED BY DISCONNECTING ONE PREHEAT LEAD FROM EACH CATHODE AND THEN BY SWITCHING THE BALLAST ON AT THE MAXIMUM INPUT VOLTAGE OBSERVE WHETHER THE LAMPS START OR FLICKER. EITHER CONDITION WILL INDICATE THAT THE RAPID START CATHODES ARE BEING DAMAGED. WITH ALL PREHEAT LINES CONNECTED, TRY REPEATED STARTING. IF A BLUE
FLASH OR FLICKERING BLUE GLOW OCCURS AT EITHER END OF THE LAMP, THE CATHODES ARE BEING BOMBARDED BEFORE REACHING THE PROPER TEMPERATURE FOR A NORMAL START. THERE ARE OF COURSE, MORE SOPHISTICATED TESTS TO OBTAIN A COMPLETE ANALYSIS OF THE STARTING CONDITION, BUT THE FOREGOING TESTS ARE INDICATORS.

Prototype designs of high frequency ballasts should be checked with accelerated starting along with a control test of standard ballasts on the same schedule. This should then be followed with a normal life test for a good statistical analysis.

HIGH FREQUENCY INSTANT START BALLASTS

Instant starting of fluorescent lamps would of course be more desirable than rapid starting or the preheat method, using starters. Instant start 40 watt lamps with a special cathode are still available, but the corresponding ballast is considerably larger, less efficient, and higher in cost than the rapid start system. For these economic reasons, the 60Hz instant start system was relegated to certain special applications or where reliable starting at low ambient temperatures was required. Also the 60Hz instant start ballasts, have a poor noise rating and probably would not be applied to commercial lighting or areas of low ambient noise.

A 25KHz branch circuit frequency converter could operate instant start lamps including the slimline types without any of the foregoing problems. Fig. 29 illustrates the various com-

-55-
ponents of the system with the choice of two ballast circuits.

Four lamp rapid start, or four lamp instant start. The rapid start system requires a preheat transformer and capacitor in each ballast and a lower voltage input. The simplest, lowest cost and most efficient ballast is the instant start capacitor ballast on a series sequence circuit with starting voltage distributed from the Frequency Converter. In the process of producing the high frequency, a transformer is generally used in the semi-conductor switching circuit. The same transformer secondary winding is designed to produce the starting and operating voltage which is then distributed to the individual fixtures containing the appropriate ballasts.

lighting fixtures

All of the high frequency systems to date have utilized conventional 60Hz fluorescent fixtures with high frequency ballasts. If these energy efficient systems are applied in large quantities, a more cost effective fixture is possible by tailoring the design to match the small size, light weight and low loss high frequency ballasts. Lighter gauge metal, smaller ballast channels and simplified wiring added to the lower cost ballast should bring about a significantly lower cost fixture.

Conventional fixtures must be designed to dissipate the heat loss of the 60Hz ballast which has been 15 to 20% of the total fixture input watts. (New premium, higher efficiency 60Hz magnetic ballasts were introduced in 1978 with losses of approximately 10%). The heat loss in most 60Hz enclosed fixture designs
WILL RESULT IN AN INCREASE IN LAMP BULB WALL TEMPERATURE AND REDUCED LUMEN OUTPUT OF THE LAMPS AND FIXTURE. AN INSTANT START HIGH FREQUENCY SYSTEM USING CAPACITOR BALLASTS WILL HAVE A LOSS OF ONLY ABOUT 1%. IN ADDITION TO PROVIDING FOR MAXIMUM LIGHT OUTPUT, NO METAL STARTING AID IS REQUIRED FOR HIGH FREQUENCY INSTANT STARTING. THIS GIVES THE MANUFACTURER FREEDOM TO DESIGN FIXTURES USING NON-METALIC MATERIALS. EXTRUDED PLASTIC IS A POSSIBILITY IF LOWER IN COST THAN STEEL. DUE TO THE LIGHT WEIGHT BALLASTS, THE SHIPPING COST OF THE FIXTURES CAN ALSO BE REDUCED.

WIRING

IN THE PREVIOUSLY DESCRIBED 360, 420, 840 AND 3000HZ SYSTEMS, WITH A CENTRALLY LOCATED FREQUENCY CONVERTER, NORMAL 60HZ WIRING IS APPLIED. THE LEADING POWER FACTOR OF THE LOAD COUPLED WITH THE INDUCTIVE REACTANCE OF THE LINE RESULTS IN A POSITIVE CHANGE IN VOLTAGE EVEN WITH THE LENGTH OF LINES GREATER THAN 100'. (TABLE III IN THE REFERENCED PAPER.)

IT MAKES VERY LITTLE DIFFERENCE ELECTRICALLY WHETHER STEEL OR ALUMINUM CONDUIT IS USED AT THE RELATIVELY LOW FREQUENCIES OF 360, 420, 840 OR 3000HZ. HOWEVER, ALUMINUM CONDUIT IS PREFERRED ALONG WITH RUBBER COVERED OR OTHER SOFT MATERIAL AS INSULATION FOR THE COPPER WIRE. THE USE OF SPECIFICED MATERIALS CAN GREATLY REDUCE OR ELIMINATE AUDIBLE NOISE IN THE DISTRIBUTION LINES.

THE DISTRIBUTION OF POWER FROM BRANCH CIRCUIT, 'LOAD CENTER' FREQUENCY CONVERTERS AT 25KHZ, WILL NOT PRODUCE AN AUDIBLE NOISE PROBLEM, BUT SPECIAL WIRING AND SHIELDING MAY BE REQUIRED TO
PREVENT EXCESSIVE VOLTAGE DROPS AND POWER LOSSES SO INDUCED VOLTAGES WILL NOT ENTER OTHER BUILDING WIRING OR EQUIPMENT. THE 'LOAD CENTER' SYSTEM HAS THE ADVANTAGE OF COMPARATIVELY SHORT POWER LINES, MAKING IT POSSIBLE TO SERVICE AN AREA OF 100' X 100' WITH A FOUR-WAY DISTRIBUTION OF 50' FROM A SINGLE FREQUENCY CONVERTER OR PROPORTIONALLY SHORTER LINES FROM SEVERAL CONVERTERS.

SWITCHGEAR

IN THE 420HZ MOTOR GENERATOR OR TOTAL ENERGY GAS TURBINE SYSTEMS, SLIGHTLY DERATED 60HZ BREAKERS ARE GENERALLY USED AT THE BRANCH CIRCUIT PANEL. (14 AMPERE 420HZ VS. 15 AMPERE 60HZ). SELECTIVE SWITCHING IS ACCOMPLISHED BY MEANS OF FUSES WITH SWITCHING RELAYS.

THE 3000HZ SYSTEM HAS A LIGHTING DISTRIBUTION PANELBOARD WITH CIRCUIT BREAKERS CALIBRATED FOR 3000HZ OR FUSED SWITCHES WITH THE FUSES DERATED FOR 3000HZ.

A 'LOAD CENTER' 25KHz SYSTEM WITH D.C. DISTRIBUTION FROM A CENTRAL RECTIFIER COULD USE D.C. BREAKERS OR FUSES ON THE PRIMARY SIDE AND FUSED RELAYS FOR SELECTIVE SWITCHING OF FIXTURES ON THE 25KHz OUTPUT.

RECOMMENDATIONS

IN THE SEARCH FOR AN OPTIMUM LIGHTING SYSTEM WHICH IS BOTH ENERGY EFFICIENT AND COST EFFECTIVE, THE PRECEDING REVIEW OF HIGH FREQUENCY SYSTEMS, SERVED TO DELINEATE THE ADVANTAGES, DISADVANTAGES AND PROBLEMS EXPERIENCED OVER THE PAST 27 YEARS.
THE OBJECTIVE OF THIS STUDY IS TO DETERMINE WHETHER ADVANCES IN ELECTRONIC TECHNOLOGY AND NEW DEVICES, ARE NOW SUFFICIENT TO JUSTIFY DEVELOPMENT OF A NEW LIGHTING SYSTEM, FOR MAXIMUM EFFICIENCY AND APPLICATION FLEXIBILITY IN THE OPERATION OF FLUORESCENT AND HIGH INTENSITY DISCHARGE LAMPS.

THE CONCEPT DESCRIBED IN THE PRECEDING PAGES UNDER THE HEADING "MODULAR BRANCH CIRCUIT CONVERTERS" IS PROPOSED AS A POSSIBLE WAY TO MEET THE OBJECTIVE WITH TECHNOLOGY AND DEVICES AVAILABLE TODAY.

POWER TRANSISTORS WITH HIGH CURRENT AND VOLTAGE RATINGS ARE NOW AVAILABLE FOR USE IN FREQUENCY CONVERTER DESIGNS TO PROVIDE UPWARDS OF 10 K.W. AT 25KHZ. CIRCUITS USING POWER TRANSISTORS REQUIRE FEWER COMPONENTS THAN THE S.C.R. CIRCUITS PREVIOUSLY EMPLOYED AND COST PER K.W. SHOULD BE LOWER.

SOME MANUFACTURERS ARE BUILDING POWER TRANSISTOR INVERTERS AND FREQUENCY CONVERTERS FOR OTHER PURPOSES, WHICH CAN BE MODIFIED AND ADAPTED FOR USE IN LIGHTING. POWER EFFICIENCY RANGES FROM 92% TO 95% DEPENDING ON OUTPUT RATING IN SIZES OF 5 TO 15 K.W.

IT IS RECOMMENDED THAT ANY STUDY OF THE BRANCH CIRCUIT OR 'LOAD CENTER' FREQUENCY CONVERTERS INCLUDE THE FOLLOWING;

1. DESIGN SELECTIVE OUTPUT LOAD SWITCHING.
2. DETERMINE WHETHER SYSTEM AND COMPONENTS WILL MEET UNDERWriters REQUIREMENTS.

*BRANCH CIRCUIT CONVERTERS WOULD BE LOCATED AT OR NEAR THE FLOOR SWITCH PANEL IN THE HALLWAY OR WIRING CLOSET. A 'LOAD CENTER' INVERTER WOULD BE LOCATED IN THE CENTER OF AN AREA IN A CEILING MODULE OR PARTITION WITH DISTRIBUTION IN 4 DIRECTIONS.
3. Conduct appropriate tests on rapid start ballasts to determine whether the lamp is starting properly. See Component Section "High Frequency Rapid Start Ballasts".

4. Make E.M.I. tests to determine whether the system meets F.C.C. rules and regulations.

5. Make comparative overall efficiency tests to determine gain over best 60Hz lamp and ballast system, including the electronic ballasts.

6. Complete cost analysis of all components to determine system economic feasibility.

7. Design power management system for remote control of input power and light output as an adjunct to the power supply.

It is also recommended that fluorescent lamp manufacturers consider development of an optimum fluorescent lamp for high frequency operation in the range of 20 to 40KHz. From the preceding information, an instant start type would be preferred for both branch circuit and individual two and four lamp electronic ballasts. It is thought that changes can be made in lamp design to significantly increase lamp efficacy within the frequency range mentioned above.

From past experience it would be highly desirable to develop the system around a complete package or a systems approach for installation so all specifications are followed. Comprehensive testing of all components for performance characteristics, followed by a demonstration of an application would also be recommended.
CONCLUSIONS

The extensive survey and review of previous high frequency central lighting systems, and the proposed branch circuit multi-fixture system yield the following conclusions:

Early systems such as the motor-generator sets providing 420 and 840Hz, demonstrated economy and efficiency gains at the time over conventional 60Hz fluorescent lighting. High voltage distribution and efficient small, light weight ballasts were key features of high frequency power.

However, to update the motor-generator system and make it competitive by today's standards would require a much higher frequency to obtain an increased lamp efficacy. The cost of distributing large blocks of power at 10KHz or higher would be excessive.

The total energy gas turbine generation provides a relatively low electrical energy cost, because the input power furnishes heat and air conditioning from the normally wasted heat of the prime mover. Performance of this system at the Northern Illinois Gas Co. over 17 years of operation indicates that it is still a viable energy efficient lighting method, but future installations will depend upon an increase in gas supplies.

The 3000Hz silicon controlled rectifier frequency converters had some difficult problems involving audible noise and lamp starting difficulties. When all of the components were made
AND INSTALLED ACCORDING TO THE SPECIFICATIONS, THE SYSTEM COULD BE QUIET IN OPERATION AND PROVIDE GOOD LAMP PERFORMANCE. A COMPLETELY ENGINEERED PACKAGE WAS NEEDED, BUT DIFFICULT FOR ONE MANUFACTURER TO ASSEMBLE AND MARKET DUE TO THE NUMBER OF COMPONENTS IN THE SYSTEM. A NUMBER OF RELATIVELY LARGE INSTALLATIONS WERE MADE, AND THE ENERGY SAVING QUALITIES OF THE SYSTEM WAS DEMONSTRATED. HOWEVER, THE PROBLEMS OF AUDIBLE NOISE AND COST OF MAINTENANCE RESULTED IN ABANDONMENT OF 3000Hz LIGHTING.

THE LOAD CENTER 25KHz BRANCH CIRCUIT SYSTEM PROPOSED IN THIS REPORT WOULD PROVIDE SILENT OPERATION AND SHORT LINE DISTRIBUTION OF THE HIGH FREQUENCY POWER, SMALL LOW COST BALLASTS, HIGH OVERALL EFFICIENCY AND SIMPLIFIED POWER MANAGEMENT ON A LIMITED RANGE. THE INCENTIVES FOR PLANNING AND DESIGNING THE BRANCH CIRCUIT LIGHTING SYSTEM, INCLUDE THE LARGE SAVING IN POWER COMPARED TO CONVENTIONAL OR PREMIUM HIGH EFFICIENCY 60Hz LIGHTING, THE AVAILABILITY OF COMPONENTS FOR DEVELOPMENT AND DESIGN OF THE INVERTER, D.C. DISTRIBUTION AND SMALL LOW LOSS LAMP BALLASTS. LIGHTING FIXTURES ARE SIMPLIFIED DUE TO THE USE OF CAPACITOR BALLASTS AND THE DISTRIBUTION OF THE REQUIRED STARTING VOLTAGES. RE-DESIGN OF FIXTURES FOR LOWER COST CAN ADD APPRECIABLY TO THE OVERALL ECONOMIC GAINS OF THIS PROPOSED HIGH FREQUENCY LIGHTING SYSTEM.
SOURCES FOR THE ILLUSTRATIONS USED IN THIS REPORT ARE HEREBY GRATEFULLY ACKNOWLEDGED.

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Increased efficiency results when fluorescent lamps are operated at higher frequency.

Fig. 2

Increased light output and higher wattages are obtained with higher frequency operation.

Fig. 3

Basic circuit in magnetic frequency multiplier has three main elements: frequency tripler stage, frequency doubler stage and limiter stage.

Fig. 1

The two magnetic frequency converters in use at the Department of Agriculture's Beltsville project for supplying 360-cycle current to an installation of 88 T8 lamps. The lower drawing is a block diagram of the frequency converter.

Fig. 4
CLOSE spacing of fluorescent lamps in this experimental room required locating the ballasts for the 60-cycle system in an adjoining corridor. This required additional wiring to all the lamps.

LAMP ballasts line corridor, emit considerable heat not wanted in plant room.

PLANT room installation shows the close spacing of the fluorescent lamps with the capacitor ballasts (about the size of a pack of cigarettes) mounted above them. Small size, light weight, and little heat loss are some advantages of this system. Only two wires required to bring power from converters to all lamps. Illumination can be adjusted for 1600 to 2400 ft-c; the 60-cycle system is necessarily fixed at about 1600 ft-c.
TEST installation in this room is proving the value of adjustable light output with magnetic frequency multipliers. As dust on reflectors cuts down lumen output a small potentiometer (left) is set to increase lamp current. Lamp output can be increased automatically by means of photoelectric control so it is not necessary to clean reflectors between relampings.

Fig. 6
Designer takes a close-up look at one of the light-weight luminaires that give high light level without direct glare.

UNION COLLEGE Alumni Memorial Field House, Schenectady, New York has the first major installation of high frequency fluorescent lighting system. This is operated on 400-cycle power by means of two rotating-type frequency converters. The Field House covers an area of 49,000 square feet, and employs 35 fixtures, each eight feet square, and containing 14 eight-foot slimline lamps. A maintained footcandle level of about 45 is obtained. Fixtures in the center row are 60-ft. from floor level; end rows are 34-ft. from the floor.

Fig. 7
400 CYCLE 600 V GENERATOR CONNECTIONS

Fig. 9A
POWER CONVERTER is 30 kva unit, transforms 3-phase, 3-wire, 440-volt, 60-cycle power (motor, left), into 3-phase, 6-wire, 400-volt, 840-cycle power.

WIRING arrangement for secondary 840-cycle distribution, which is a 3-phase 6-wire system, 400 volts per phase, with 200-volts to ground from any phase leg. Generator windings are center-tapped and grounded. Lamp load is serviced at full 400 volts, so that only 18 circuits are required for the 580 lamps used.

Per cent efficiency increase vs frequency for 24-inch, 48-inch and 96-inch lamps of T12 diameter. Lamps were held at their 60-cycle rated watts over entire frequency range. Points on the 360-cycle line show per cent increase in efficiency when lamps are operated on a square current wave.

MODULAR treatment of lighting system and all interior components—plastic diffusers, acoustical baffles, metal partitions, air diffusers, sprinklers, etc.—permits maximum flexibility of office layout and arrangement. This area is reception lobby, with offices of Pres. A. F. Wakefield and president’s secretary visible in background.
Figure 15: Two-lamp rapid start schematic (top) and wiring diagram (bottom)

Figure 16: Two-lamp Slimline fixture wiring - 420Hz
Figure 17: Switching for lighting branch circuit - 4 ft. lamp

Figure 18: Open delta generator circuit - 8 ft. lamp
Bus equipped with experimental transistor inverter providing 3000 cycles for 42T6 slimline lamps. The 16 lamps are operated on eight two-lamp ballasts weighing only three-quarters of a pound each. Lighting levels range from 25 to 35 fc. By contrast the filament lighting system measured from 4 to 12 fc.

Twenty-pound transistor inverter is shown at right. In left foreground are eight two-lamp 3000-cycle ballasts stacked next to the same number of 60-cycle two-lamp ballasts. Sixty-cycle inverter (not shown) would be required if bus had been equipped with conventional ballasts (left background).

Size comparison—variable frequency ballast (foreground) vs. 60-cycle ballast.

![Graph](image)

Characteristics curves 42-inch T-6 slimline lamp.

![Diagram](image)

Motor coach power supply

![Diagram](image)

Variable frequency starting and operating circuit.

Fig. 19

Fig. 20

p. 72
(left) "ell" type inverter, (right) output wave shapes for "ell" type inverter.

High Frequency Power Source—Johnson-Winpisinger-Roessel

ILLUMINATING ENGINEERING

Block diagram of transistorized high frequency lighting system.

High frequency lead-lag 40-watt rapid start ballast.

Converter block diagram.

1½ kw transistorized high frequency converter shown at top of picture. Standard 60-cycle ballast cans in black compared to 1500-cycle ballast size in light color. From left to right: 2-lamp, 8-foot, 1500 ma ballast; 2-lamp, 8-foot, 800 ma ballast; 2-lamp, 4-foot, 430 ma ballast.

Fig. 21
INVERTER BALLAST RAPID START

Figure 1b. Single transistor basic rapid-start circuit.

INVERTER BALLAST SWITCH START

Figure 1a. Basic single transistor circuit for operation of fluorescent lamps from batteries or dc power supplies.

Table I—Characteristics of Various Fluorescent Lamps at 15,000 Cycles per Second with an Inverter Ballast Compared with 12-Volt Filament Lamps at Several Wattages

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<tr>
<th>LAMP TYPE</th>
<th>NOMINAL LENGTH OF BULB</th>
<th>INITIAL LUMENS 60 HERTZ</th>
<th>INITIAL LUMENS 15 KILOHERTZ</th>
<th>NOMINAL LAMP WATTS</th>
<th>APPROXIMATE INPUT WATTS</th>
<th>LUMENS PER AMPERE AT 12 VOLTS</th>
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<td>44.0</td>
<td>43.7</td>
<td>525</td>
</tr>
<tr>
<td>F16T10, CW</td>
<td>16-inch outside</td>
<td>9300</td>
<td>2460</td>
<td>40</td>
<td>53.3</td>
<td>46.3</td>
<td>550</td>
</tr>
</tbody>
</table>

* At 600 ma

Fig. 22
SCR frequency converter without moving parts, which converts 60-cycle 3-phase 208- or 230-volt to 20-kW 3000-cycle single-phase power; efficiency approximately 90 per cent, weight 25 lb/kW.

Main components of 25-kW SCR frequency converter.

Fig. 23

Schematic circuit diagram of the 4-lamp 40W Rapid Start 3000 cycle ballast.

Fig. 24

Figure A. 40W Rapid Start Lamp Efficiency vs. Frequency. 3000 cycle point represents a square current wave form, other points are with a sine wave of current. Lumen measurements have been taken at the same lamp watts for each frequency.

Figure B. 40W Rapid Start Lamp Lumens Per Watt Including Ballasts. 60 cycle ballast is conventional series sequence. All other frequencies are with capacitor ballasts in series sequence.

Figure C. 40W Rapid Start Lamp Lumens per System Watt With 60 Cycle Lamp and Ballast as 100%. Points on the curve for all other frequencies include losses in ballasts and frequency converter.

Fig. 25
### STEEL CONDUIT VOLTAGE CHANGES

<table>
<thead>
<tr>
<th>Wire Size</th>
<th>Line Current</th>
<th>R</th>
<th>X_L</th>
<th>Voltage Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 Volts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10,000</td>
<td>.276</td>
<td>.600</td>
<td>2.23</td>
</tr>
<tr>
<td>12</td>
<td>10,000</td>
<td>.438</td>
<td>.648</td>
<td>1.39</td>
</tr>
<tr>
<td>14</td>
<td>10,000</td>
<td>.692</td>
<td>.692</td>
<td>-1.16</td>
</tr>
<tr>
<td>10</td>
<td>15,000</td>
<td>.276</td>
<td>.600</td>
<td>3.29</td>
</tr>
<tr>
<td>12</td>
<td>15,000</td>
<td>.438</td>
<td>.648</td>
<td>2.00</td>
</tr>
<tr>
<td>10</td>
<td>20,000</td>
<td>.276</td>
<td>.600</td>
<td>4.32</td>
</tr>
</tbody>
</table>

| 600 Volts |              |     |      |                |
| 10        | 10,000       | .276| .600 | 2.26           |
| 12        | 10,000       | .438| .648 | 1.44           |
| 14        | 10,000       | .692| .692 | -1.08          |
| 10        | 15,000       | .276| .600 | 3.36           |
| 12        | 15,000       | .438| .648 | 2.12           |
| 10        | 20,000       | .276| .600 | 4.46           |

### ALUMINUM CONDUIT VOLTAGE CHANGES

<table>
<thead>
<tr>
<th>Wire Size</th>
<th>Line Current</th>
<th>R</th>
<th>X_L</th>
<th>Voltage Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 Volts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10,000</td>
<td>.248</td>
<td>.480</td>
<td>1.60</td>
</tr>
<tr>
<td>12</td>
<td>10,000</td>
<td>.394</td>
<td>.520</td>
<td>.82</td>
</tr>
<tr>
<td>14</td>
<td>10,000</td>
<td>.612</td>
<td>.550</td>
<td>-.55</td>
</tr>
<tr>
<td>10</td>
<td>15,000</td>
<td>.248</td>
<td>.480</td>
<td>2.36</td>
</tr>
<tr>
<td>12</td>
<td>15,000</td>
<td>.394</td>
<td>.520</td>
<td>1.18</td>
</tr>
<tr>
<td>10</td>
<td>20,000</td>
<td>.248</td>
<td>.480</td>
<td>3.10</td>
</tr>
</tbody>
</table>

| 600 Volts |              |     |      |                |
| 10        | 10,000       | .248| .480 | 1.62           |
| 12        | 10,000       | .394| .520 | .86            |
| 14        | 10,000       | .612| .550 | -.50           |
| 10        | 15,000       | .248| .480 | 2.42           |
| 12        | 15,000       | .394| .520 | 1.26           |
| 10        | 20,000       | .248| .480 | 3.20           |

— sign indicates voltage drop

### Ampere Capacity at 3000 Cycles

<table>
<thead>
<tr>
<th>Wire Size</th>
<th>60 Cycle Rated Amperes*</th>
<th>Aluminum Conduit</th>
<th>Steel Conduit</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>30</td>
<td>29.6</td>
<td>28.2</td>
</tr>
<tr>
<td>12</td>
<td>20</td>
<td>19.8</td>
<td>18.8</td>
</tr>
<tr>
<td>14</td>
<td>15</td>
<td>14.9</td>
<td>14.1</td>
</tr>
</tbody>
</table>

* Allowable current carrying capacity of insulated conductor at 60°C or 75°C temperatures.

---

**Figure 26**

**Figure 8b. A branch circuit power supply.**

**Figure 8a. An integral power supply.**
Preliminary Economic Comparison 40 Watt Rapid Start Lamp
Relating the 3000 C.P.S. System with a Typical 60 C.P.S.
Lighting System

<table>
<thead>
<tr>
<th>Building Without Air Conditioning</th>
<th>A 60 C.P.S. (Present Cost)</th>
<th>B 3000 C.P.S. (Potential Cost &amp; at Rated Lamp Current)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative initial cost</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>Burning hrs. per year</td>
<td>2500</td>
<td>4000</td>
</tr>
<tr>
<td>Relative operating cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5¢ per KWHR</td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td>2¢ per KWHR</td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td>Total annual cost</td>
<td>1.5¢ per KWHR</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>90</td>
</tr>
<tr>
<td>Building With Air Conditioning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative initial cost</td>
<td>100</td>
<td>98</td>
</tr>
<tr>
<td>Burning hrs. per year</td>
<td>2500</td>
<td>4000</td>
</tr>
<tr>
<td>Relative operating cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5¢ per KWHR</td>
<td>100</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>84</td>
</tr>
<tr>
<td>2¢ per KWHR</td>
<td>100</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>84</td>
</tr>
<tr>
<td>Total annual cost</td>
<td>1.5¢ per KWHR</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>89</td>
</tr>
</tbody>
</table>

* Estimated cost for frequency converter, ballasts and fixtures have been conservatively reduced to correspond with expected increased use of high frequency systems. Ballasts can be designed to operate lamps at rated current resulting in loading to 44 watts with the square current wave form provided at 3000 cycles. The additional lumens obtained account for some of the reduced initial and annual costs between columns A and B. Tests now being conducted will determine the feasibility of lamp operation at 44 watts.

Fig. 28

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High Frequency Lighting System
Load Center Distribution
Rapid Start or Instant Start
Ballasts

Fig. 29
Preliminary Economic Comparison 40 Watt Rapid Start Lamp
Relating the 3000 C.P.S. System with a Typical 60 C.P.S.
Lighting System

Building Without Air Conditioning

<table>
<thead>
<tr>
<th></th>
<th>60 C.P.S. (Present Cost)</th>
<th>3000 C.P.S. (Present Cost)</th>
<th>3000 C.P.S. (Potential Cost &amp; at Rated Lamp Current)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative initial cost</td>
<td>100</td>
<td>110</td>
<td>100</td>
</tr>
<tr>
<td>Burning hrs. per year</td>
<td>2500</td>
<td>4000</td>
<td>2500</td>
</tr>
<tr>
<td>Relative operating cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5¢ per KWHR</td>
<td>100</td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td>2¢ per KWHR</td>
<td>100</td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td>Total annual cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5¢ per KWHR</td>
<td>100</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td>2¢ per KWHR</td>
<td>100</td>
<td>100</td>
<td>94</td>
</tr>
</tbody>
</table>

Building With Air Conditioning

|                | 100                      | 98                          | 93                                                   |
| Burning hrs. per year | 2500                     | 4000                        | 2500                                                 |
| Relative operating cost  |                           |                             |                                                     |
| 1.5¢ per KWHR | 100                      | 100                         | 84                                                  |
| 2¢ per KWHR   | 100                      | 100                         | 84                                                  |
| Total annual cost  |                           |                             |                                                     |
| 1.5¢ per KWHR | 100                      | 100                         | 91                                                  |
| 2¢ per KWHR   | 100                      | 100                         | 90                                                  |

* Estimated cost for frequency converter, ballasts and fixtures have been conservatively reduced to correspond with expected increased use of high frequency systems. Ballasts can be designed to operate lamps at rated current resulting in loading to 44 watts with the square current wave form provided at 3000 cycles. The additional lumens obtained account for some of the reduced initial and annual costs between columns A and B. Tests now being conducted will determine the feasibility of lamp operation at 44 watts.

Fig. 28

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2. "High Frequency Adapts Fluorescent Lamps to Aircraft" by R.F. Hayes, Electrical Engineering, Vol. 60, P. 530, November 1941. (Limited to small lamps at 400 Hz.)


30. RUSSIAN PAPER (NO TITLE IN TRANSLATION) BY G.K., DIPLOMA PROJECT, MEI, 1960.


33. "PROGRESS IN STATIC CONVERTERS FOR HIGH FREQUENCY FLUORESCENT LIGHTING", W.H. JOHNSON, JUNE 1961, ILLUMINATING ENGINEERING.


35. "HIGH FREQUENCY LIGHTING, EQUIPMENT, CONCEPTS, PRACTICES", R. HORNER, SEPTEMBER, 1961, ACTUAL SPECIFYING ENGINEER.


44. "Frequency Converter Based on Thyatrons for High-Frequency Fluorescent Lamps", G.H. Gorbachev, V.A. Labuntsov and Yu, I Fadeyev. Svetotekhnika 12, January 1966, p. 1-4


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