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TRANSACTIONS (TM)

ELECTROMAGNETIC INTERFERENCE FROM ELECTRICAL POWER SYSTEMS IN SHIPS

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Electromagnetic Interference from Electrical Power Systems in Ships

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SYNOPSIS

This paper reports an investigation into electrical interference in the frequency range from 10 kHz to 30 MHz generated by ships' electrical appliances. The main sources of interference presented in this paper are localized in synchronous generators, excitation and voltage-control systems, thyristor phase-control systems, converters and main electrical drive systems.

INTRODUCTION

Electromagnetic protection has taken on increased importance because of the intensive development of communication and data transmission systems and the increase in the amount of electrical and electronic equipment in use. The problem is of particular importance in ships, which have a limited amount of space and a high density of electromagnetic equipment producing interference as an undesirable by-product.

A ship's equipment must be compatible with the radio noise from the electrical equipment. This noise must not exceed the levels specified by regulations and national and international standards. These levels are related to the magnetic and electric fields and to asymmetric noise voltages. The fields are insignificant as propagation by radiation is difficult because the compartments are screened and the equipment is protected from the marine environment by tight metal casings. Interference with electrical equipment is therefore caused mainly by asymmetric noise voltages of low attenuation propagating from the ship's electric power lines.[1]

Even a single source of noise in a network may influence the levels of interference in the whole system if sensitive devices are fitted. The introduction of thyristor systems has considerably increased the amount of interference. An example of the use of these systems is a fishing vessel with thyristor circuits in the main drive system as well as thyristor excitation and voltage control for the synchronous generators.

It has therefore become necessary to investigate and identify the noise characteristics and sources of interference in ship's electrical systems. Such investigations are being undertaken at the Institute of Marine and Industrial Electrotechnology of the Technical University of Gdansk. The investigations cover:

- Synchronous generators.
- Excitation and voltage-control systems of synchronous generators.
- Thyristor phase-control systems.
- Controlled bridge rectifiers and inverters.
- Propulsion drive systems.

Krzysztof Fagiewicz was born in 1940 and since 1963 he has been employed as a researcher and lecturer at the Institute of Marine and Industrial Electrotechnology of the Gdansk Technical University. He has been engaged in ship's electrotechnology since 1967, with particular attention concentrated on thyristor systems, and has carried out many research programmes in this field, the results of which have been implemented in the shipbuilding industry. Dr Fagiewicz is the author of many scientific papers and in 1971 he received a doctorate following his thesis on 'Sources of radioelectrical interference in thyristor systems'.

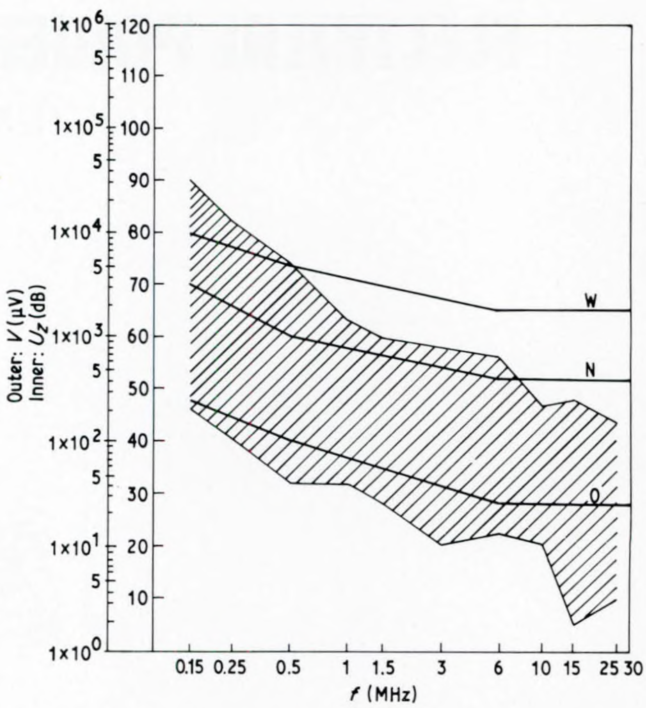

FIG. 1 Ranges of maximum interference voltages (of three phases) produced by synchronous generators with separate excitation. Results for 18 generators of 27–800 kVA for $P = (0.1–1)\,P_N$, $\omega = \omega_N$ and $\cos\phi = 0.8$. W, N and O are specified limits of interference according to Refs 5 and 6

The investigations were initiated by the shipbuilding industry when new electrical equipment was being fitted in ships. The investigations could only be of an experimental nature, and in order to obtain comparable and reproducible results standard conditions had to be used.[2,3] Analytical determination of generated disturbances is not easy because of the lack of data on high-frequency parameters relating to ships' electrical equipment. This makes it impossible to apply methods of equivalent sources of frequency spectra and to use Maxwell equations, which require numerous simplifying assumptions leading to approximate solutions with errors. The level of the errors is higher than the level of the interference. In addition, there is difficulty in determining the boundary conditions and it is impossible to assess the effect of interference on the analysed system parameters. Thus a theoretical analysis has not been carried out.[4]

The first stage of the investigation dealt primarily with

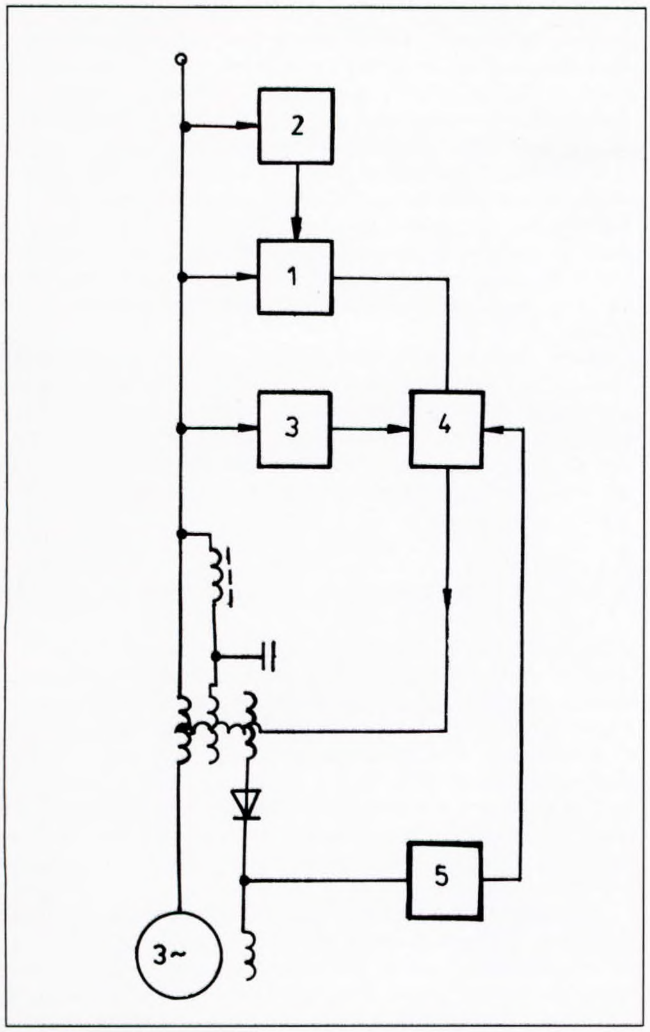

FIG. 2 Block diagram for a controlled-phase excitation system of the RMDC type: 1, measuring and comparison element; 2, current compensation device; 3, power pack for amplifier; 4, preliminary amplifier; 5, stabilizing circuit

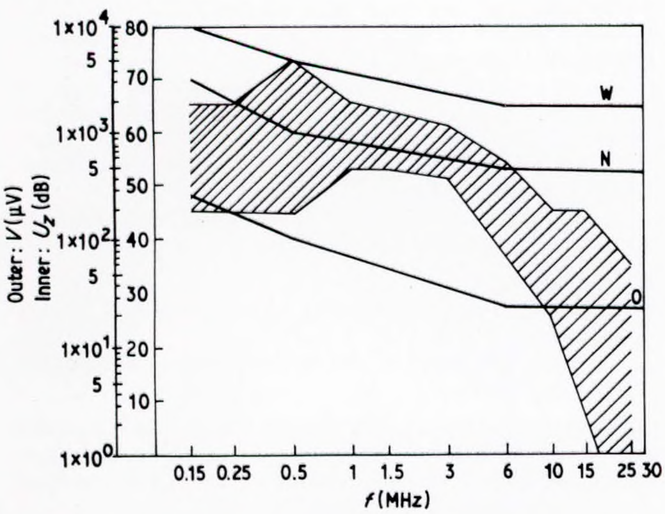

FIG. 3 Maximum limits of radio interference voltages (out of three phases) of compound voltage regulation systems with magnetic amplifiers and brushless generators circuits (see Fig. 2). Results for 10 generators of 27–90 kVA for $P = (0.1–1)\ P_N$, $\omega = \omega_N$ and $\cos \phi = 0.8$. W, N and O are permissible interference limits according to Refs 5 and 6

components of high-frequency asymmetric interference in the frequency band from 0.15 to 30 MHz. Because of the development of transmitting systems such as radio navigational aids, mobile and stationary services, radio-location, and the control and registration of data, low-frequency disturbances in the 10–150 kHz range also had to be included in the investigation.

SYNCHRONOUS GENERATORS

The main source of disturbances in generators is the collector ring brush, which supplies electric current to the excitation circuit. Generators produce various levels of interference which are dependent on the angular velocity of the generator, the pressure of the contact brush against the ring, the quality of the insulation, the vibrations of the shaft and factors such as worn rings and misalignment of the shaft. It has been proved that asymmetric interference produced by generators is generally not at a high level.[5,6]

Exploitation factors also affect the magnitude of the generated disturbances, and cases have occurred of generators which, after a period in service, showed lower levels of interferences than when new. This may have resulted from wear and tear of the sliding ring-brush complex or the oiling up of rings.

Some typical ranges of interference produced by generators are shown in Fig. 1.

EXCITATION AND VOLTAGE-CONTROL SYSTEMS OF SYNCHRONOUS GENERATORS

The level of interference from excitation and voltage-control systems depends on the amount of noise contained in the unit and the amount of disturbance from the excitation circuit transmitted into the network. The investigations have shown that equipment can be divided into three groups for generated interference, the grouping being independent of the use of the equipment.

Low interference

This group comprises systems with non-controlled rectifiers and magnetic amplifiers, as well as brushless generator circuits (see Figs 2 and 3).

Medium interference

This group comprises systems with regulation of the excitation current by thyristors separated from the generator's excitation circuit by transformers (see Figs 4 and 5).

High interference

This group comprises systems with the excitation circuit controlled by rectifiers without galvanic separation from the generator's excitation circuit (see Figs 6 and 7).

THYRISTOR PHASE-CONTROL SYSTEMS

In thyristor phase-control systems the levels of the generated interferences are determined by:

1. Thyristors.
2. Gate control devices.
3. Couplings, loads and thyristor suppression filters.

When connected under dynamic conditions, thyristors transfer from an interlocking to a conduction state and from a conduction to a barrier state and they are responsible for turbulent changes in voltage and reductions of current, both of which generate disturbances. The amount of interference depends to a great extent either on the thyristor switching

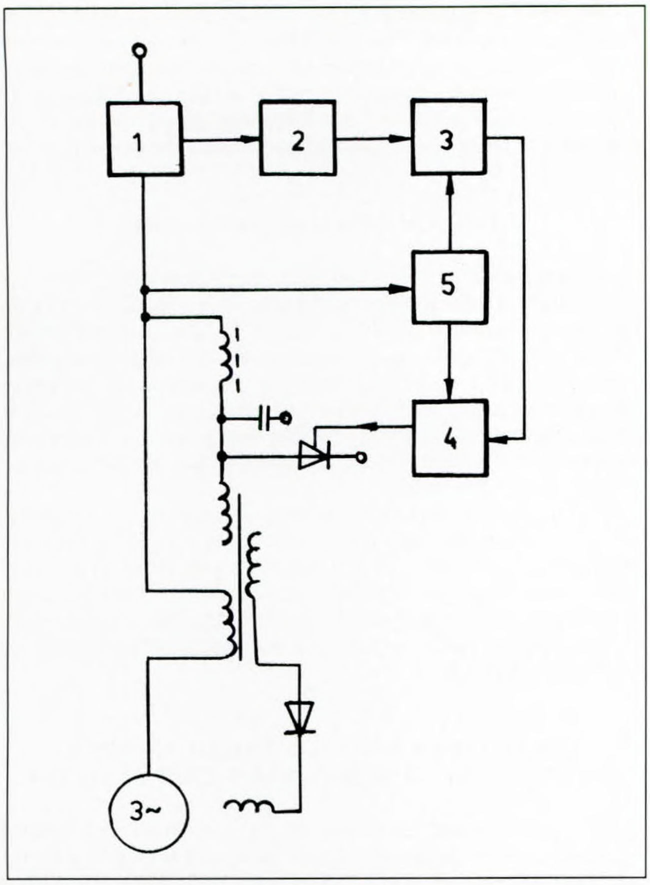

FIG. 4 Block diagram for a controlled-phase system of the WGSY-100 type: 1, current compensation system for measuring unit; 2, measuring and comparison element; 3, preliminary amplifier; 4, gate tripping circuit; 5, fuder

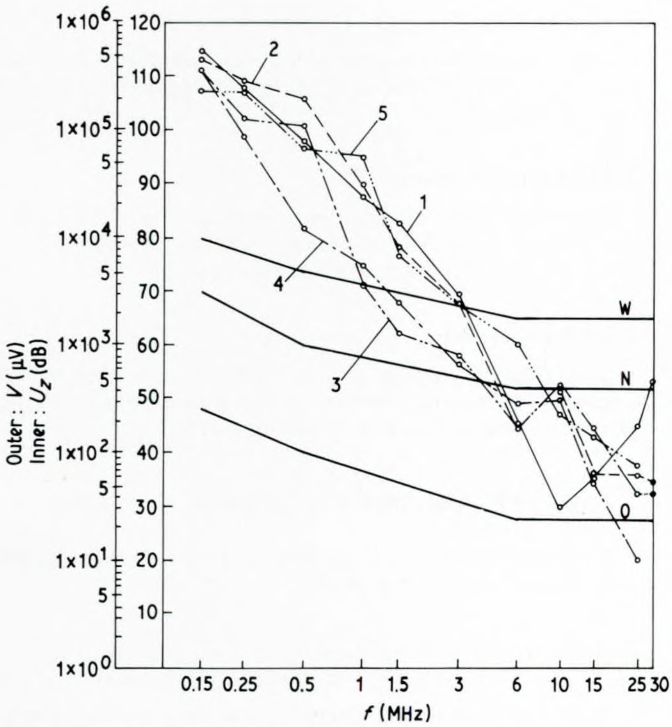

FIG. 5 Spectral characteristics of maximum interference voltages (out of three phases) of five thyristor shunt voltage regulation systems (see Fig. 4) for $P = (0.1–1)\ P_N$, $\omega = \omega_N$ and $\cos\phi = 0.8$. W, N and O are permissible interference limits according to Refs 5 and 6

voltage or, at a constant value of the supply voltage, on the gate tripping delay angle. The switching time and characteristics of the connected circuit have a significantly smaller effect on the level of the generated interferences. Typical examples of thyristor-generated noise voltages in the frequency band from 10 kHz to 30 MHz are given in Figs 8 and 9.

Gate control equipment, usually pulse systems, are a source of interference and should be taken into account when designing thyristor systems. Gate control pulses can be single or multiple and the duration of the impulse delivered to the gate within the range of anode (positive) voltages is proportional to the gate connection angle and the frequency of operation of the system.

The applied impulse (either single or multiple), the pulse rise and fall time, and the pulse repetition rate influence the magnitude of the generated disturbances. Generated noise voltages from gate tripping devices are illustrated in Figs 10 and 11. It has been found that the effect of loads and thyristor overvoltage suppression filters on the generated asymmetric noise is insignificant.

THYRISTOR CONVERTERS

In ships' systems, the thyristor converters are mainly used as control rectifiers for electrical machines in main drive systems, hoisting winches, cargo-handling facilities etc. The elements which generate the interference are the thyristor and gate control devices. The noise sources from loading converters are particularly localized in direct current electrical machines. It has been found that resistance loading of the rectifier does not affect the level of generated noise voltages, but that thyristor switching voltages and gate control appliances are of great importance.

It has also been noted that the transformer's primary circuit supplying the converter has an effect on the level of interference in the ship's power network. Experiments on inverters have proved that noise voltages in these systems depend, as with control rectifiers, on the thyristor switching voltage. Noise voltages from converter systems are shown in Fig. 12.

MAIN DRIVE SYSTEMS

Electric drive systems are fitted in ships with particular requirements for manoeuvrability and for utilizing primary sources of energy. Most use diesel–electric drive in which the primary source of energy is not responsible for the interference generated by the system.

The solutions can be sub-divided, dependent on the type of current used and the type of control equipment, into DC systems, AC systems and mixed systems, which are controlled either on the principle of constant current or by a Ward-Leonard device.

Analysing the systems on the basis of the localized sources of disturbance, equipment can be grouped as follows:

1. Electrical machines.
2. Thyristor converter systems in main and auxiliary current circuits.
3. Control and regulation systems connecting measuring and signalling apparatus.

Electrical machines used in main drive systems are amenable to a number of solutions which are not available for standard equipment such as double armature circuits, special bearing designs and sliding commutator-brush nodes.

DC commutator machines are the most common sources of high levels of interference because of current variations in the commutating coil circuits and variable sliding-brush contact with the commutator. In conventional machines additional electromagnetic phenomena frequently occur because of operation at constant armature current independent of the machine

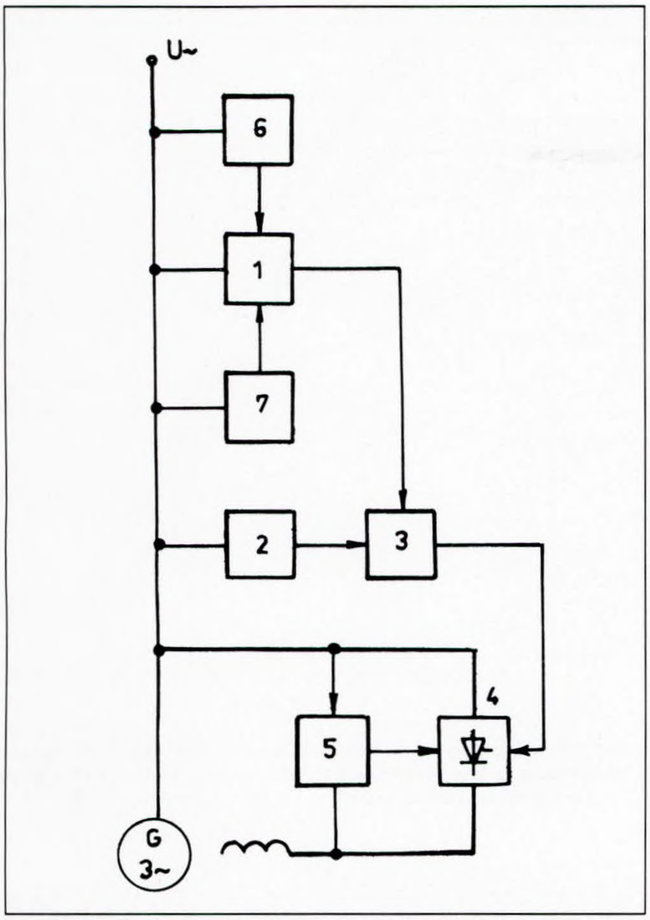

FIG. 6 Block diagram for a system of the TUR type: 1, control circuit; 2, fud; 3, gate control gear; 4, thyristor excitation rectifier; 5, initial excitation circuit; 6, current compensation device; 7, reduction of excitation current

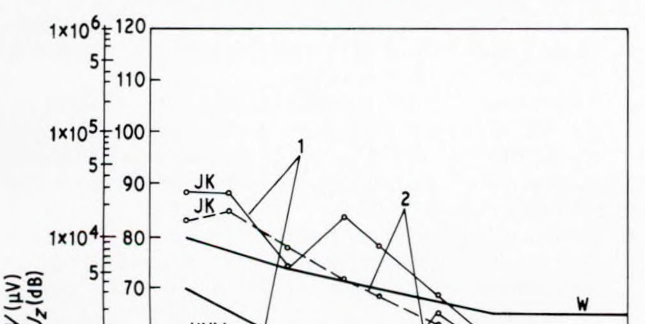

FIG. 7 Special characteristics of maximum interference voltages (out of three phases) of two thyristor compound voltage regulations systems (see Fig. 6). Curve 1, generator 1; Curve 2, generator 2; I and K, excitation circuit; UVW, armature circuit. W, N and O are permissible interference limits according to Refs 5 and 6

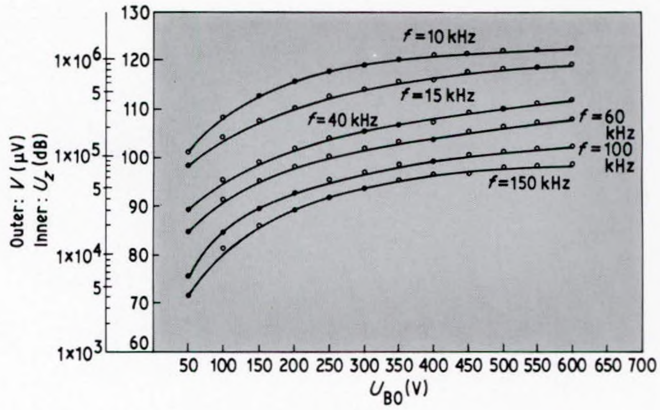

FIG. 8 Interference voltages within the frequency range 10–150 kHz as a function of thyristor constant-voltage switching

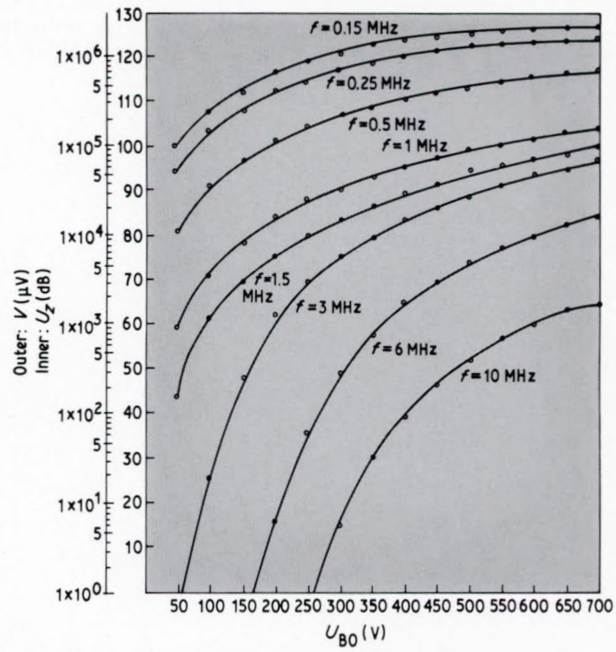

FIG. 9 Interference voltages within the frequency range 0.15–10 MHz as a function of thyristor constant-voltage switching

load (constant-current principle) and vibrations from the combustion power plant.

The control-circuit connections, feedback signal processing and input limitations first reveal themselves in the form of temporary impulse interference generated under manoeuvring conditions. The duration and repetition rate of these impulses, which are known as rogues, are irregular and of secondary importance in existing drive systems. Thyristor systems with low-frequency bands have been found to be primarily responsible for interference in ships' main propulsion systems, while high-frequency bands affect electrical machines.

The experimental nature of the investigations required many tests to be carried out in ships, at manufacturers' testing stations, and in laboratories. This made it possible to identify the basic sources of interference in ships' electrical equipment and enabled corrective action to be taken at an early stage in the design. It also enabled the old system, which required construction first and then testing to get rid of the observed disturbances in the equipments, to be superseded. Modifying equipment in service results in delays and increased costs.

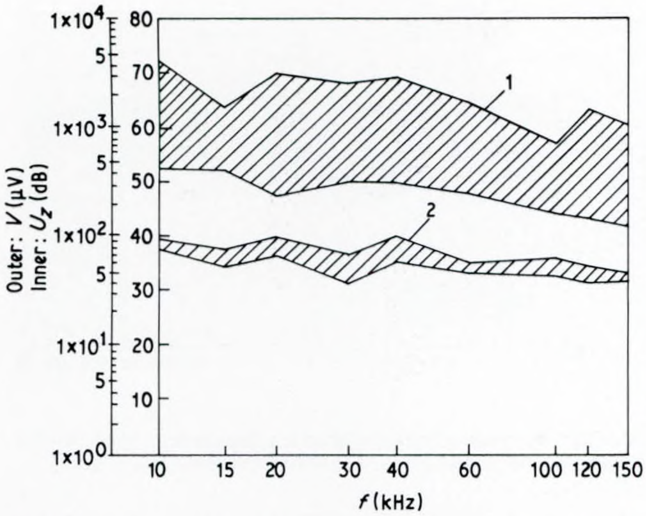

FIG. 10 Levels of noise voltages in the frequency range 10–150 kHz for a thyristor gate control system generating single and multiple pulse trains at a gate cathode voltage of 1 V and duration 20 ms. Area 1, multiple pulses of repetition rate 0.2–5 kHz; area 2, single pulses

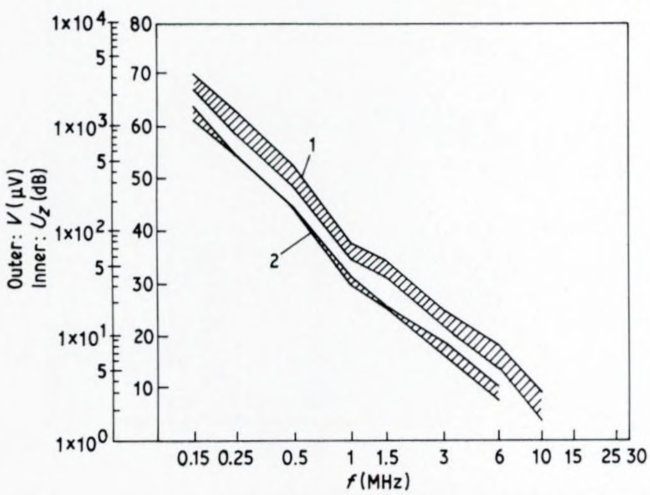

FIG. 11 Levels of noise voltages in the frequency range 0.15–30 MHz for a thyristor gate control system generating single and multiple pulse trains at a gate cathode voltage of 1 V and duration 20 ms. Area 1, multiple pulses of repetition rate 0.2–5 kHz; area 2, single pulses

CONCLUSIONS

The investigations have resulted in a number of important suggestions, which are not applicable solely to ships, for designers of thyristor systems. The most important include:

1. Electrical circuits with phase-controlled thyristors in the frequency band from 10 kHz to 30 MHz are sources of asymmetric interference, the amount of which is dependent on the thyristor switching voltage.
2. In various thyristor connection circuits (control rectifiers, AC converters and inverters), interference levels comparable with the levels of interference generated by a single controlled-phase thyristor circuit were noticed.

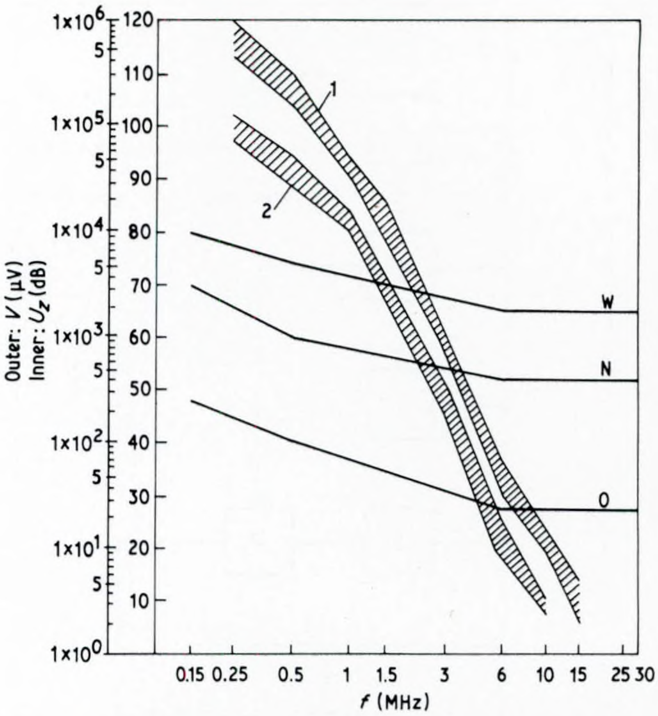

FIG. 12 Maximum levels of noise voltages in the frequency range 0.15–30 MHz of the three controlled rectifiers at $V = 380$ V and $I = 25$, 60 and 70 A. Area 1, $\alpha_W = 90°$; area 2, $\alpha_W = 30°$

3. The levels of the generated noise voltages were almost independent of the magnitude and character of the load in the range of resistance and induction loadings investigated.
4. The levels of the generated noise voltages can be determined empirically using thyristor circuit data obtained at the supply network frequency.
5. The thyristor systems (lower-frequency noise voltages) and DC electrical equipment (higher-frequency bands) are mainly responsible for the generated noise voltages in electric power systems supplying the ship's network and the ship's main propulsion.
6. Noise sources localized within equipment must be taken into account when designing electrical systems and to avoid interference it may be necessary to separate some of the supply lines.
7. In view of the correlation between thyristor switching voltages and generated interference levels, measurements on thyristor systems should be carried out at the maximum thyristor switching voltages.
8. Investigations to estimate the anticipated levels of interference should be carried out early in the design of the ship's electrical equipment as it is expensive to modify systems once they have been manufactured and installed.
9. Interference-suppression systems will not adversely affect the strength and reliability of thyristor devices, although suppression systems can affect connection and recovery times of semiconductor elements, which may result in a short circuit in the system.
10. Disturbances in a ship's electrical system should be investigated in depth and the filtration elements should be considered as being capable of affecting other systems via the electric power network and the ship's hull.

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Discussion

J. K. ROBINSON (Lloyd's Register of Shipping): Would the author please clarify the meaning of the W, N and O limits in Polish Standards and if the figures show measurements of conducted interference?

Does the author know of any radiated interference problems arising from ships' power systems in the 30 to 300 MHz frequency range?

IEC 34 Rotating electrical machines, Part 1: Rating and performance, in section 11—Irregularities of waveform, specifies in some detail telephonic harmonic factor limits up to 5 kHz. It is known that the installation of thyristor converters often results in system THF in excess of these limits. Has the author made measurements of conducted interference below 10 kHz and is he aware of in-service problems on internal voice communication circuits or programmable electronic controls arising from interference in this frequency range?

J. H. DHINGRA (Mobil Shipping Co. Ltd.): I should like to thank Dr Fagiewicz for bringing to our attention the silent menace of electromagnetic interference which has been overlooked for a long time. Needless to say, the identification of noise characteristics and sources of interference is essential when building modern UMS class ships with computerised controls, and I fully agree with the view of the compatibility of ships' systems with radio noise from electrical equipment. However, I would like to suggest that the control equipment should also be compatible with the radio waves produced by communication equipment, viz. UHF sets, data transmitters etc. in or around the machinery space.

I would now like to describe the menace created by interference from radio waves experienced recently in two new UMS class ships. UHF sets were being used for communication from the engine room to deck in a tanker during routine repair work, night rounds of engine room or fire drills etc. It was found that whenever it was used near the main engine turbocharger it energised a high-temperature alarm thereby slowing down the main engine automatically.

In the beginning a lot of time and labour was wasted trying to find the fault in the main engine operation systems until the cause was identified as the walkie-talkie. The temperature sensor was picking up the radio signals and then sending a signal to the PCB in the control room. A lower value capacitor was then inserted in the PCB (still meeting the requirements) and no more interference was observed.

Another incident occurred using Motorola near an oxygen analyser installed in an inert gas system, leading to incorrect readings being obtained.

I would appreciate Dr Fagiewicz's comments on the feasibility and effectiveness of the following measures in existing ships:

1. Screening and protection should be adequate to absorb the radio waves, as well as providing protection from the marine environment.
2. Installation of RF protectors.

R. C. COOMBES (Ministry of Defence): The paper presents a broad view of the problem of electromagnetic interference from electrical generation and control systems and its findings/conclusions are generally in accordance with RN ship experience.

The synopsis states that the investigations are based on a bottom frequency limit of 10 kHz whilst all of the graphs, with the exception of Figs 8 and 9, show results from 150 kHz. Below 150 kHz, levels of interference from thyristor-controlled plant increase theoretically by 6 dB/octave with the possibility of coupling to data processing, sonar, telephone, intercommunication and other low-frequency systems.

Considering only the asymmetrically generated conducted interference is acceptable as this represents the worst case situation. Radiated emissions are not considered. As stated in the introduction, direct radio frequency radiation from electrical plant to susceptible machinery in metallic ships does not generally present a problem due to the inherent compartment and equipment screening.

Interference current flowing in power system cabling can however couple with adjacent susceptible cables unless installations are carefully planned. The known techniques of cable segregation and screening need to be exploited.

Traditionally, electrical generating plants have been considered to be producers of interference but to be immune from interference. However, the widespread use of electronic control systems has introduced susceptibility problems. For example transients on supply lines can shut down a generator.

Thyristor converters used to power large dc motors generate high levels of interference particularly at frequencies below 2 MHz. Large magnetic fields are associated with the power cables due to the high currents involved. These fields can couple with any adjacent low-frequency systems unless suitable precautions are taken in the installation.

Installation of power generation systems on non-metallic ships poses additional problems not only in respect of interference generation and propagation but also of susceptibility.

Conclusion 10 draws attention to an effect that is not widely known, ie interference suppressors fitted to the three-phase supply lines of thyristor rectification equipment can behave as three single-phase units operating cyclically. In a four wire system the majority of the live current would return via the neutral. In a three wire unearthed system the capacitance to hull in conjunction with other capacitances to hull would create a neutral path via the ship's structure. Common mode current can be significantly enhanced in the frequency range below 100 kHz and will only be reduced by the removal or reduction of the 'to hull' capacitance.

The specified levels of interference indicated on Figs 1, 3, 5, 7 and 12 at W, N and O are not recognised; however, the interference level N approximately equates to the limits used by the Royal Navy. Generally electrical power supply systems below 650 volts for RN Ships have to be in accordance with Defence Standard 61-5 Part 4.

Author's reply

In reply to Mr Robinson, the notations W, N and O mean the maximum specified levels of asymmetric terminal voltage interference permissible according to the Polish Standard PN-69/E-2021 and the Polish Register of Shipping. Level W is permissible for electrical equipment installed under a main deck, Level N is permissible on the main deck, and level O over the main deck, for example the supply of a radio room.

The figures show measurements of conducted interference.

I have investigated interference in the 30 to 300 MHz frequency range. In ships this is not so important because of the steel panels used to separate compartments etc, and which also protect against radio interference. In Poland, the level of radio interference on a ship in the 30–300 mHz frequency range is not limited.

I have not investigated radio interferences in the range below 10 kHz. I am aware of in-service problems with internal voice communication circuits and programmable electronic controls, because during my work I encountered harmful interactions on such equipment caused by conducted interference below 10 kHz. I intend to examine radio interference below 10 kHz in the near future.

I agree with Mr Dhingra about the compatibility of ship's control systems with radio noise produced by communication equipment, data transmitters etc. In my work I have encountered signal deformation as a result of radio interference. Compatibility of all a ship's systems should be considered at the design stage, but it can be done by people with experience of this problem.

I also agree with Mr Dhingra about the screening and protection required to absorb radio waves and protecting RF installations from radio noise.

I agree with Mr Coombes that my conclusions are generally based on ship's electrical equipment. However, Figs 8 and 9 have meaning for all thyristor structures with the same turn-on time. From Figs 8 and 9 it does not follow that levels of interference increase by 6 dB/octave for the 10–150 kHz frequency range. The level of interference increases by 6 dB/octave only when the turn-on time is zero, which is not true for real thyristor devices. In fact I have not presentred the levels of interference for thyristor controlled plant below 150 kHz, but it is possible to obtain the equation $U_Z = F(f)$ from Fig. 8. When we have a turn-on voltage U_{BO}, we can find U_Z as $U_Z = F(f)$ when U_{BO} = constant.

When a thyristor device is working with another device, for example a synchronous generator, we obtain characteristics relevant to the thyristor device. The synchronous generator can change the resultant character of interference because the generator is also a source of noise.

Interference can be a reason for a signal's deformation, and so cable segregation and screening are necessary.

The paper does not mention problems of interference fields and interference suppressors. I agree that the problem of interference fields is important on non-metallic ships but is too big a problem to be presented in one paper.

The specified levels of interference indicated on Figs 1, 3, 5 and 7 are from the Polish Standard PN-69/E-2021, and the Polish Register of Shipping.