THE TYPE 23 COMBINED TEST FACILITY

PART I: DEVELOPMENT AND INSTALLATION

BY

R. E. JENNINGS, M.PHIL., M.SC., C.ENG., M.I.E.E., R.C.N.C.
(*on secondment from the Ministry of Defence to Yarrow Shipbuilders Ltd.*)

Introduction

This article is the first of two devoted to the Type 23 frigate Combined Test Facility (CTF) and describes its development and installation. Part II will cover the testing and analysis of results.

The schematic diagram of the CTF in FIG. 1 shows that it contains one half ship set of the Type 23 electrical power and propulsion system. The major elements of the complete Type 23 system are shown in FIG. 2.

From the outset, the CTF had to be a cost-constrained facility and hence many of the features of a traditional shore development facility had to be radically reviewed and changed to achieve the tight budget placed on Yarrow Shipbuilders Ltd. (YSL) by the MOD. The features reviewed included:

(*a*) purpose built accommodation;
(*b*) large numbers of staff;
(*c*) extended testing period;
(*d*) comprehensive instrumentation;
(*e*) large scale sub-contractor support.

The spirit of reviewing all areas to achieve minimum cost can be illustrated by the fact that the whole facility was installed, set to work and tested under a tent in the main car park at the National Engineering Laboratory, East Kilbride. However, although YSL and its sub-contractors have been unstinting in their approach to economic solutions, the technical achievements of the project have been far less constrained than the cost, and indeed some technical achievements have equalled in many areas those of earlier shore development facilities.

The 'Raison d'être' of the Combined Test Facility

An initial assessment of the Type 23 power system design against those run by large power utilities such as the Central Electricity Generating Board will reveal an incredible simplicity. In fact, continuing on the theme of an initial appraisal, one could forgive most engineers for reaching the conclusion that in view of the technical achievements of the large power utilities the design of a system such as that shown in FIG. 2 would represent a relatively trivial, low risk design. This assumption would be incorrect for, although in power network terms the system is indeed simple, the operational and fault tolerance requirements have demanded the development and use of power system design techniques that are rarely required in the domain of large integrated power networks.

As an example of this (from a wide range of problems that faced the system and equipment designers) two system operational requirements will be discussed to aid an appreciation of the risks associated with using the best of current design techniques to analyse the transients associated with these system requirements.

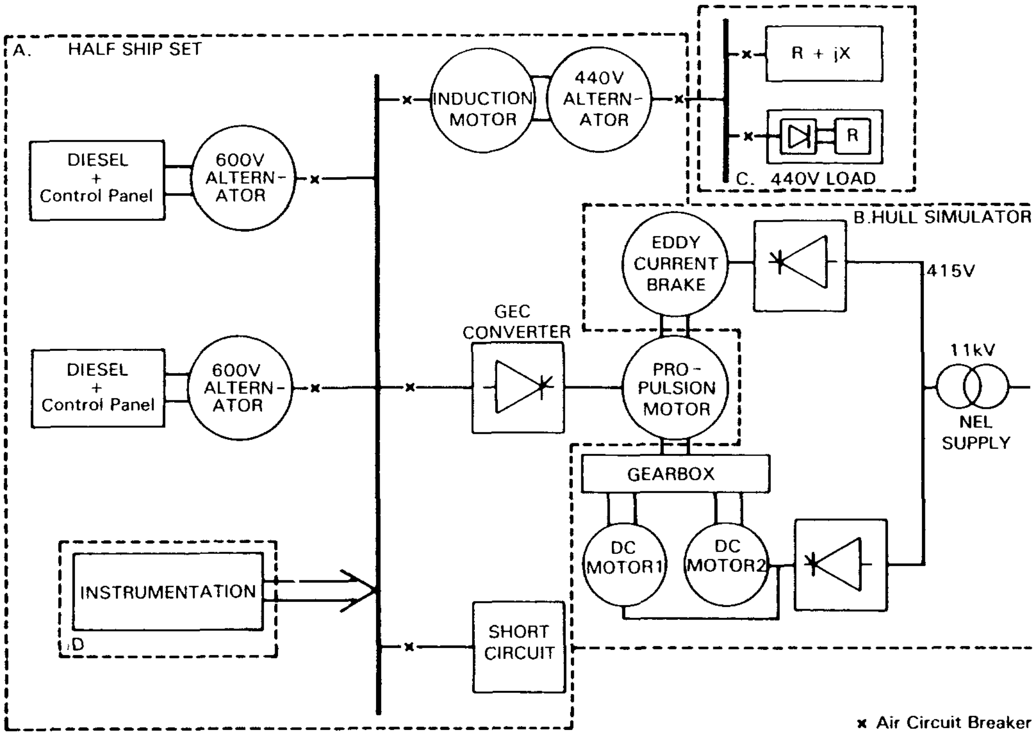


FIG. 1—COMBINED TEST FACILITY FOR TYPE 23

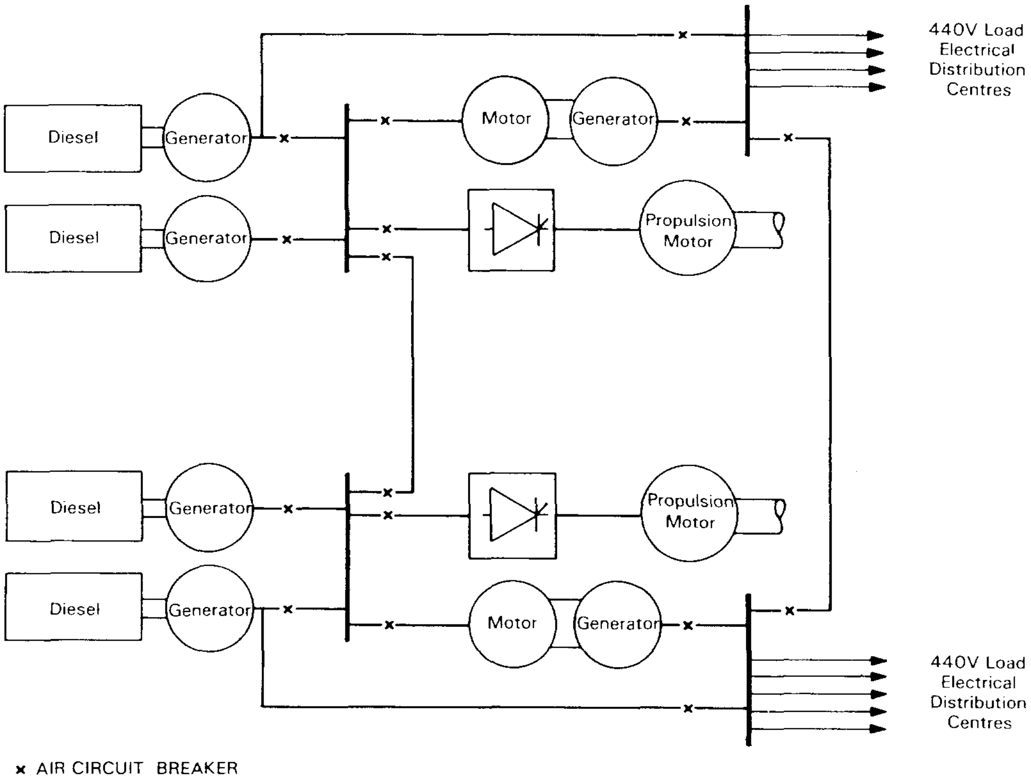


FIG. 2—TYPE 23 ELECTRICAL POWER AND PROPULSION SYSTEM

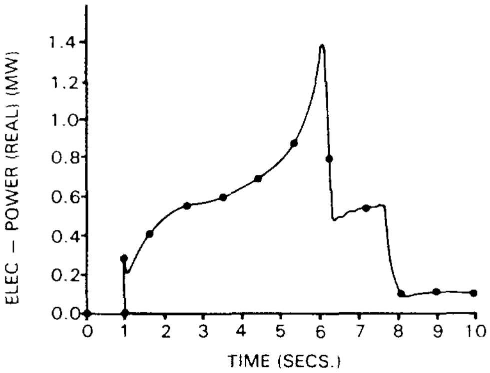


FIG. 3—POWER DEMAND FOR MOTOR-GENERATOR START

The first requirement to be considered is the starting of a motor-generator (MG) set when only one diesel generator (DG) set is operating. The DG set is rated at 1300 kW and the induction motor driving the 440 V generator is 945 kW. The starting characteristic of an induction motor is severe and under direct on-line starting condition the initial starting current can reach a level of between 6 and 8 times full load current; although much of the initial volt-amperes drawn from the generator is reactive at times the real power or kilowatt demand can be as high as twice full power rating. A typical transient power demand for starting the MG set is shown in FIG. 3. All designs are based on deriving the physical process involved, and for this particular transient the problem that faced the system designers was to try to develop a mathematical model of the diesel engine, governor, alternator, AVR and induction motor that would respond in a correct way to the power transient shown in FIG. 3. The accurate mathematical modelling of a diesel and governor is a notoriously difficult task; at best the designer can expect to receive from the equipment manufacturer models that can only give an accurate assessment for relatively small power perturbation. Using these small signal models under the power transient conditions prevailing for an MG start can lead to significant design errors.

The second operational requirement is that associated with the regenerative braking of the shaft during a crash-stop manoeuvre. To understand this complex operation it is necessary to remember that the Type 23 does not have controllable pitch propellers or reversing gearboxes and there is only the propulsion motor that can supply the braking energy required to stop the ship.

The shaft power developed by a d.c. machine is given by the following equation:

$$\text{Power} = K' N I_a I_f$$

where K' = constant
N = shaft rotational speed
I_a = motor field current
I_f = armature field current

This equation shows that the three quantities, rotational speed, field current and armature current, control the magnitude and direction of power flowing either into (braking mode) or out of (power drive mode) the shaft. FIG. 4 shows a very simplified arrangement of the power electronics used in the control of the armature and field current of the Type 23 propulsion motor. The armature (rotor) of a separately excited d.c. machine (propulsion motor or PM) always represents the main energy-carrying part of the machine; i.e. over 97% of the energy taken from the a.c. supply system is transferred through the armature bridge. This factor means that the armature thyristor control bridge tends to be constructed using expensive high power thyristors embedded into heat sinks which require forced cooling circuits. Hence there is only one armature bridge, which means that current is mono-directional. The four quadrant operation of the propulsion motor can best be understood by considering the diagram shown in FIG. 5. The most crucial part of the

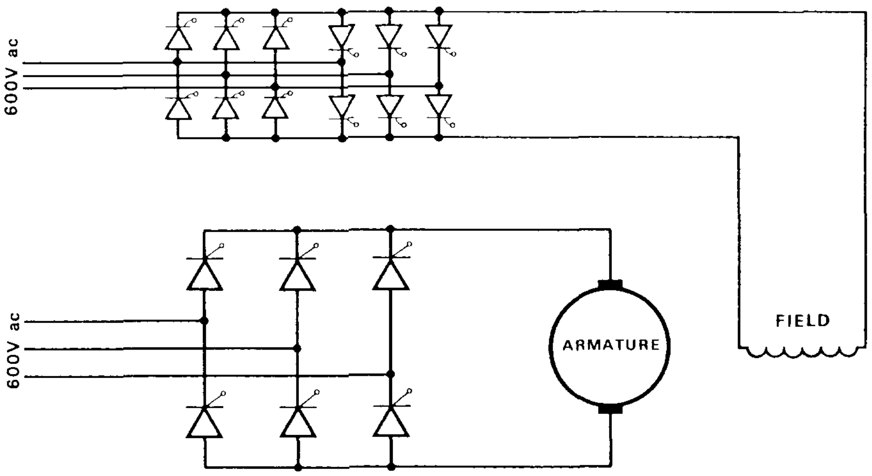


FIG. 4—PROPULSION MOTOR POWER CONTROL

emergency stopping procedure involves the regenerative braking region. During this phase of operation the field current has been reversed in polarity but the shaft speed and armature current are still in the positive direction. This means that the PM is acting as a d.c. generator and the armature thyristor bridge is acting as a line-commutated invertor which converts d.c. into three phase a.c. Thus within a few seconds the PM moves from being a heavy load on the a.c. system to that of being a major supply of a.c. power, the diesels having been virtually backed off to their idle position. Everything associated with the regenerative braking is complex—from the thyristor regulator designed to control it to the high and varying levels of a.c. supply voltage distortion that accompany this transient.

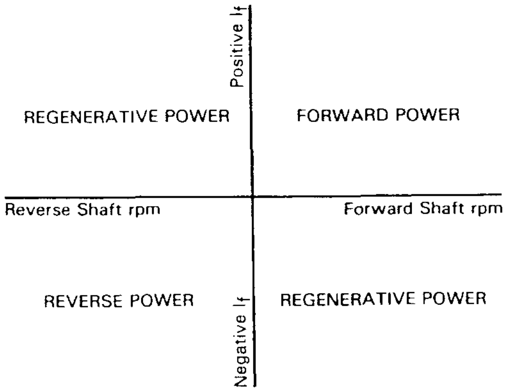


FIG. 5—FOUR QUADRANT OPERATION OF PROPULSION MOTOR

These two examples are cases from a much larger number where the design techniques available to analyse operational or fault scenarios have been stretched to their limits. The *raison d'être* for the CTF thus covered four main areas:

(*a*) To ensure that the dynamic and steady state performance of the Type 23 electrical power and propulsion system meets all design performance targets under both normal and fault conditions.

(*b*) To ensure that the quality of power supplies for the 440 V power system meets all the requirements under a very wide range of non-linear load conditions (i.e. for weapon, communication and static frequency changer (SFC) based equipment).

(*c*) To build up a powerful data base in the above two areas that can be used ultimately to facilitate improved design codes.

(*d*) To commission and test full scale Type 23 hardware using techniques and instrumentation systems that would be extremely difficult to install within a space-constrained frigate.

Combined Test Facility Hardware Review

A simplified representation of the main elements of the CTF is given in Fig. 1. This shows four major areas of hardware:

(*a*) Items within the dotted boundary marked A are the main hardware elements from half a ship set of the Type 23 electrical power and propulsion equipment.

(*b*) Items within dotted boundary B represent the hull simulator, a device designed to give the full range of propeller torques that the shaft could see during ship-based electrical power propulsion drive.

(*c*) Items within dotted boundary C represent the 440 V load test facilities.

(*d*) Items within dotted boundary D represent the instrumentation system to be described fully in part II of this article.

The basic concept of the Type 23 has already been covered in previous issues of the *Journal*[1, 2, 3] and so this article will concentrate on the hardware items specifically designed for the CTF.

The basic function of the hull simulator is to ensure that at all times the propulsion motor sees a load torque that will equal the propeller torque for all possible shaft and ship speeds within the range of the electrical propulsion drive. The concept of ship speed at a stationary test site is an important one and is defined by simulation of the ship equations of motion. These are:

$$J\frac{dW}{dt}=Q_m-Q_p \tag{1}$$

$$M\frac{dV}{dt}=T_p-kV^2 \tag{2}$$

where Q_m = motor torque
W = shaft speed
J = shaft inertia
Q_p = propeller torque which is a function of shaft and ship speed
V = ship's speed
M = ship's mass
T_p = propeller thrust which is a function of shaft and ship speed
kV^2 = hull resistance thrust

Equation 1 represents the torque equation and basically states that the rate of change of shaft speed is equal to the difference between the applied motor torque and propeller load torque. However, the propeller torque is a function of both the shaft speed and ship speed. Fig. 6 is a propeller torque versus shaft speed map for nine different forward ship speeds, whilst Fig. 7 gives the propeller torque curve for zero ship speed alone. As can be seen from these two graphs, the tests would be extremely limited if the concept of ship speed were not introduced into the test facility. The hull simulator control which does this is shown in Fig. 8. The heart of the hull simulator control system is the operation of twin microprocessor control cards. The first card takes in an input of shaft speed and, by iteratively solving a rearranged form of equations 1 and 2, produces outputs of ship speed (V), propeller thrust (T_p), propellor torque (Q_p), and calculated propulsion motor torque (Q_m). The most important output of the first processor board is the required propeller torque; this is fed to processor board 2 which has the responsibility of controlling the operation of the two d.c. motors and the eddy current brake.

Basically the second processor card has a Rom-based look-up table that defines the maximum torque capability of the eddy current brake in the four quadrants for various shaft operations. The main concept of the control is

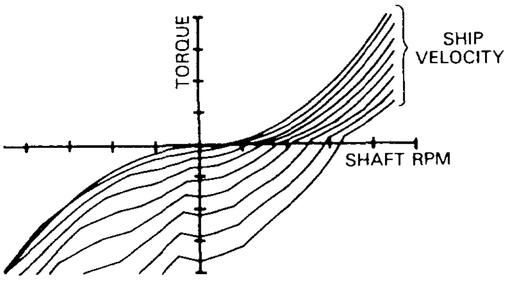


FIG. 6—TORQUE V. SHAFT R.P.M. FOR VARIOUS FORWARD SHIP SPEEDS

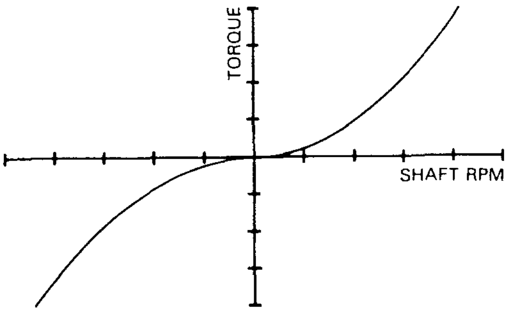
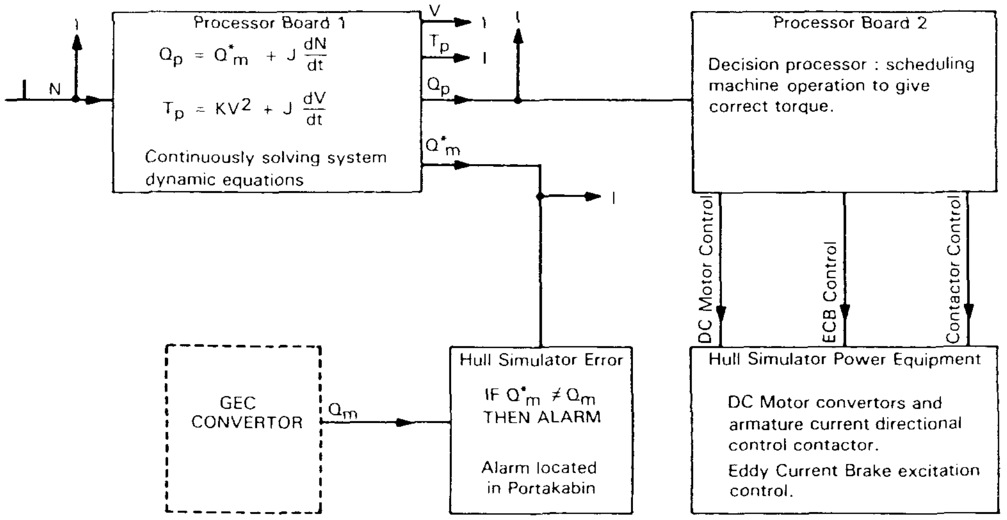


FIG. 7—TORQUE V. SHAFT R.P.M. AT ZERO SHIP SPEED

to maximize the operation of the eddy current brakes; however, if the required torque exceeds that which the brake can deliver then the control system makes good the shortfall by bringing a d.c. motor into operation. The term 'd.c. motor' should more correctly be termed 'd.c. machine' since they function as both motors and generators, depending on the quadrant of operation. For example:

(*a*) The full power of the propulsion motor exceeds the load capability of the eddy current brake; hence at full PM power about 75% of the power is being absorbed in the eddy current brake whilst the remaining 25% is being pushed into the NEL 11 kV system with one of the d.c. machines acting as a generator, regenerating energy into the a.c. system via a line-commutated invertor and transformer.

(*b*) The crash stop manoeuvre calls for a period of operation when the propulsion motor is acting as a generator taking energy from the shaft and delivering it into the Type 23 600 V a.c. system. In the ship operation this means that the propeller is acting as a water turbine driving the ship's propulsion motor. The equivalent in CTF terms is that one of the d.c. machines is acting as a motor and is turning the shaft with the ship's motor at the other end pushing this power out into the 600 V system.



N — Shaft RPM Q_m — Propulsion Motor Torque Q^*_m — Calculated Propulsion Motor Torque
Q_p – Propeller Torque T_p — Calculated Propeller Thrust V — Calculated Ship Velocity
I — Transmit Signal to Instrumentation System

FIG. 8—HULL SIMULATOR CONTROL

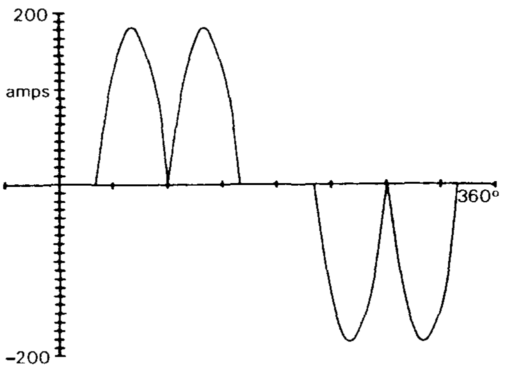


FIG. 9—TYPICAL A.C. CURRENT FOR A SONAR: LOAD CURRENT FOR ONE 60 CYCLE PERIOD

This dual operation of monitoring and generating ensures that the combination of eddy current brake and d.c. machines meets all the requirements of the simulated propeller torque.

In Type 23 operations the MG set is used to supply all the 440 V load. This load is made up of the normal mix of frigate load such as induction motors, lighting, heating, communications equipment, and weapons power supply equipment. The weapons and communications equipments represent what is called distorting load in the sense that the current that they draw from the supply is non-sinusoidal, a typical a.c. current supplying a sonar being shown in FIG. 9. The flow of such current has a two-fold effect:

(*a*) The flow of distorted current tends to produce a distorted voltage waveform, which is seen by all other load users and can lead to equipment mal-operation.

(*b*) Distorted current waveforms that are rich in harmonics, such as that shown in FIG. 9, can be the source of EMC problems.

To evaluate the performance of the Type 23 MG set—and a 600/440 V transformer being tested in the CTF as a possible alternative—a harmonic load facility has been designed based on a simple design circuit as in FIG. 10. The technical details of this work are beyond the scope of this article, but it should be stated that the data base derived as a result of this work should give powerful impetus in solving many extant weapons power supply design problems.

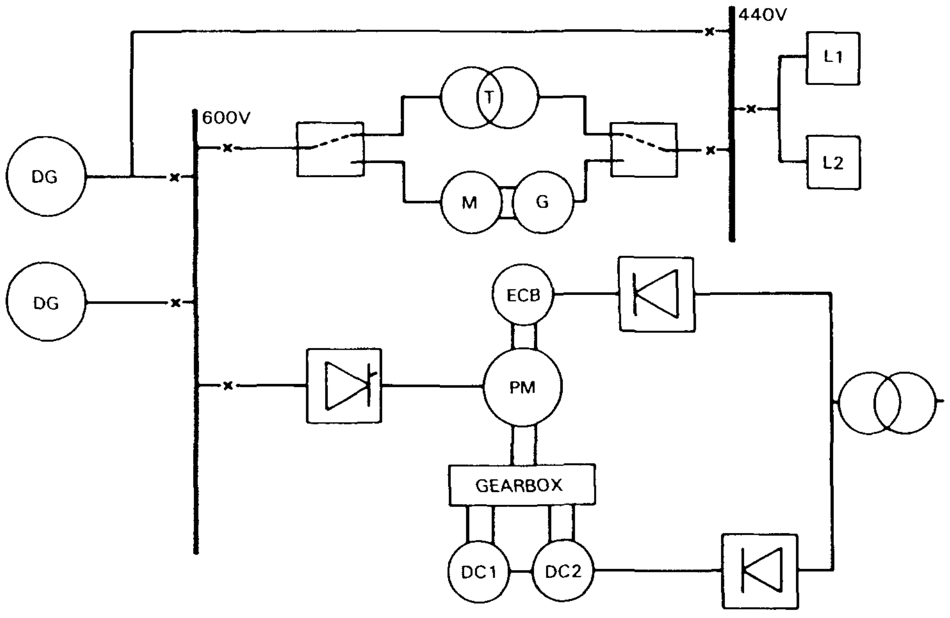


FIG. 10—CTF HARMONIC TEST CONFIGURATION

DG: diesel generator
ECB: eddy current brake
L1: 440V load bank
L2: harmonic test facility
MG: motor-generator
PM: propulsion motor

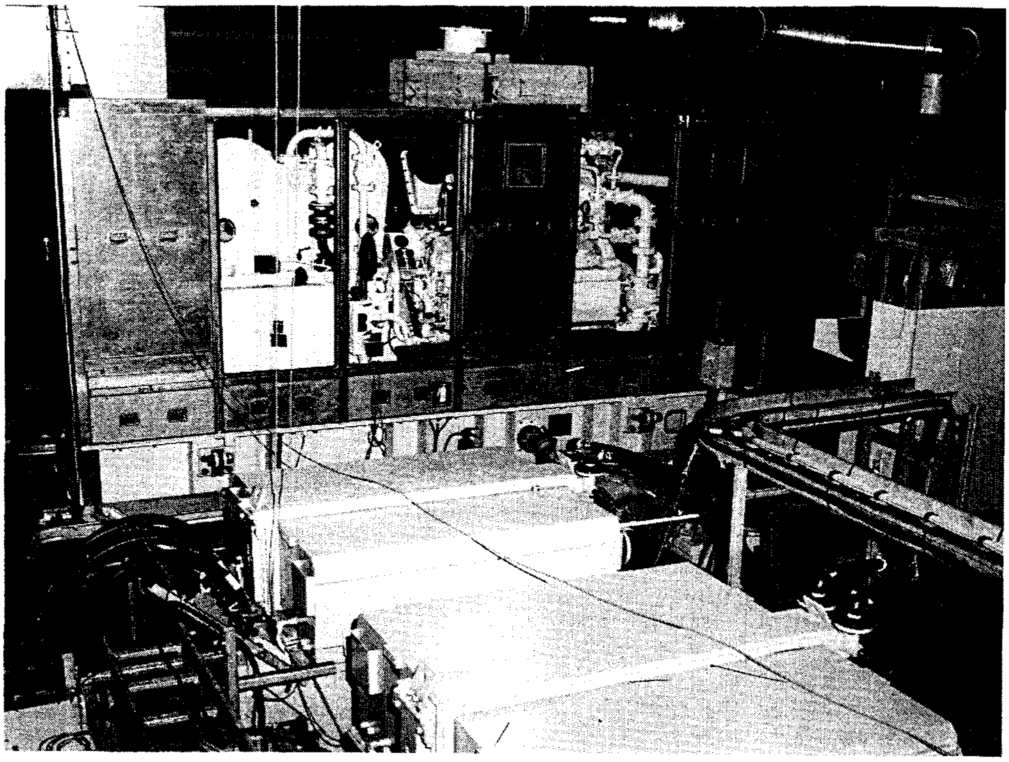


FIG. 11—MG SET (FOREGROUND) AND A MAIN DIESEL GENERATOR (BACKGROUND, WITH ACOUSTIC PANELS OPEN)

Equipment Installation

The installation of the equipment (FIGS. 11 and 12) at the NEL site was a triumph of organization, inspired thinking under trying conditions, and good old-fashioned hard work on the part of all involved. The site installation work commenced in early August 1985 with the delivery of the first diesel, and was completed by the third week in November when site commissioning began. The completion of this work included the loss of the first tented enclosure—luckily without equipment damage. It was this event which caused a three week delay in the programmed start date of the end of October for commencement of setting to work.

One of the main lessons that installing and wiring the CTF taught YSL and our sub-contractors was that the interface information in many areas left a lot to be desired. All the problems encountered at the CTF have been formally logged and each sub-con-

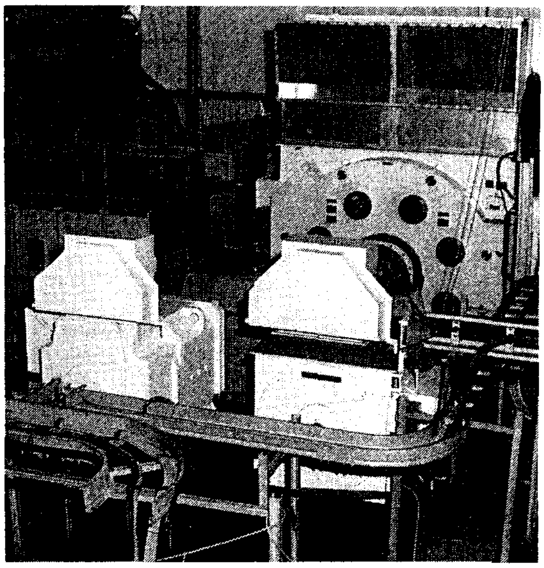


FIG. 12—PROPULSION MOTOR (BACK, RIGHT), COUPLED VIA A GEARBOX TO THE HULL SIMULATOR MACHINES

tractor will be requested to solve all CTF problems well within the timescales required for the commissioning of Type 23-01.

Summary

The Combined Test Facility provides a unique opportunity to evaluate many of the important operational aspects of an electrical system using full scale Type 23 hardware. The information gathered from this exercise will be used to ensure that the operation of the electrical power and propulsion system in Type 23-01 will meet all that is required of it and in addition show that British industry is capable of bringing together the traditional power technologies with those of advanced power electronics and microprocessor-based control to produce a system that will distinguish itself in service with the Royal Navy for many years to come.

The views expressed in this article are those of the author and are not necessarily those of the Ministry of Defence or any of the other organizations involved in the project.

References

1. Blackman, R. S.: Type 23 frigate—the engineering development; *Journal of Naval Engineering*, vol. 28, no. 1, Dec. 1983, pp. 5-15.
2. Scott, A. J.: Type 23 frigate electrical design; *Journal of Naval Engineering*, vol. 28, no. 3, Dec. 1984, pp.474-477.
3. Hawke, M. B., *et al*: The Type 23 frigate; *Journal of Naval Engineering*, vol. 29, no, 1, June 1985, pp. 15-26.