THE TYPE 23 MAIN ELECTRICAL POWER AND PROPULSION SYSTEMS

BY

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ABSTRACT

The Type 23 machinery design is such that the main electrical power and the electric motor propulsion systems are inextricably linked. Power for both is provided by the same prime movers and they are therefore required to interact. The aim of this article is to describe the major design features of the two systems and to indicate their operation with each other.

INTRODUCTION

The Royal Navy's first Type 23 frigate, HMS *Norfolk*, was accepted into service in November 1989. The Type 23 is designed as a multi-purpose warship, but its primary role is in Anti-Submarine warfare and the CODLAG (Combined Diesel Electric and Gas) propulsion system has been designed specifically to satisfy this role.

The integrated electrical systems provide power to the 440 V ship load and the electric motor d.c. load. The small number of watchkeepers in the Type 23[1] requires that the systems be designed for centralized operation and surveillance and with comprehensive protection over the full range of operating parameters. In the case of the power generation and distribution system these aims were achieved in part by the use of a D86 microprocessor system for many normal control functions. The propulsion motors, however, are controlled by regulators utilizing analogue electronic circuits to control the rate of change and the limits of motor power within the generating system capabilities.

MAIN ELECTRICAL POWER SYSTEM

The main electrical power system (MEPS) is shown diagramatically in FIG. 1. It consists of two identical power generation sub-systems feeding a variety of loads through a distribution network. Each sub-system has two 1·3 MW Paxman Valenta diesel generators (DG) feeding a 600 V bus which supplies the electric motor thyristor converter unit and a motor generator (MG) set. The 600 V system is normally operated with the interconnector breakers closed and with either two, three or four diesel generators operating in parallel. Operation of the 600 V system and the system protection necessary for the parallel operation of the generators has been described in the *Journal*[2] and that article is a useful adjunct to this one.

Two DGs are located in the Forward Auxiliary Machinery Room (FAMR) (3 and 4 deck level) and two in the Upper Auxiliary Machinery Room (UAMR) (1 and 01 deck level). To comply with the restrictions of the ship's radiated noise requirement, the lower diesels are double mounted and housed in acoustic enclosures while less stringent noise reduction measures are required for the upper diesels. Power is generated at 600 volts[3], chosen because a higher than normal (for RN) voltage offers savings in equipment cost and volume. Existing types of switchgear were capable of operation at the higher voltage without modification. Additionally, when operating with a 600 V a.c. input, the 3 phase thyristor converter provides a maximum d.c. output of approximately 810 V. Allowing for losses, this gives a usable 750 V which is a suitable level for the d.c. propulsion motor.

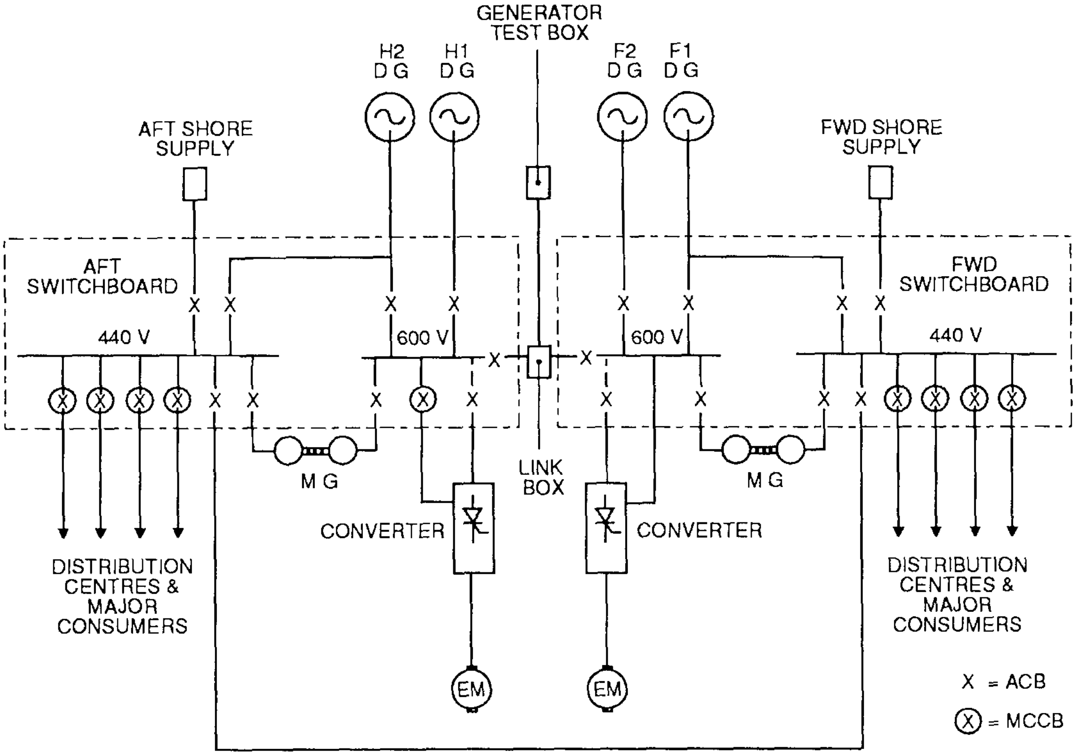

FIG. 1—TYPE 23 MAIN ELECTRICAL POWER SYSTEM

ACB: Air Circuit Breaker
DG: Diesel Generator
EM: Propulsion Motor
MCCB: Moulded Case Circuit Breaker
MG: Motor Generator

The normal power source for each 440 V sub-system is provided by a MG set fed from its associated 600 V sub-system. As well as stepping down the voltage, the motor generators isolate the 440 V system from the harmonic distortion generated by the thyristor converters on the 600 V system. The motor generators are located in the FAMR and UAMR adjacent to the diesel generators. In normal operation both MGs are run split with the 440 volt interconnector open. There is also provision for providing alternative 440 V power from one diesel generator in each sub-system and supplying this directly to the 440 V section of the switchboard in the event of a MG set failure. The 600 V and 440 V supply breakers for these diesels are interlocked to prevent inadvertent paralleling of the two systems.

Primary Electrical Control Panel

The primary electrical control panel (PECP) (FIG. 2) is in the Ship Control Centre (SCC) and is part of the Machinery Control and Surveillance (MCAS) operators' console. It consists of electrical generation and distribution panels and a dedicated D86 computer processor unit. The PECP has reflected control, primary surveillance and indications from both sub-systems of MEPS. The two sub-systems each have a Secondary Electric Control Panel (SECP) and their own dedicated D86 units. All signals passing between the PECP D86 unit and the SECP D86 units travel via duplicated (for damage control reasons) bi-directional serial data links.

No hard-wired control of electrical equipment is available from the PECP with the exception of the DG emergency stops provided on the supervisors' console and Remote or Automatic Change-Over Switch Control Indications.

The control philosophy of the PECP is that any of the four generators can be started, auto-synchronized and brought on load by the operation of the discrepancy switch, (synchronism however is not a D86 function). Conversely, they can be taken off load and the diesels shut down by the operation of the same switch. The remaining Air Circuit Breakers (ACBs) shown in FIG. 1 can all be opened or closed from the PECP, provided synchronization does not ensue, with the following two exceptions:

(*a*) 440 V I/C ACB control is not provided.

(*b*) MG set starting has to be undertaken with the DG Automatic Voltage Regulator (AVR) maximum excitation current reduced from approximately 30 amps to 20 amps. This procedure is known as 'soft starting' and is undertaken at the secondary electrical control positions in the main switchboard rooms.

Main Switchboard Rooms

Each sub-system of MEPS has a 600 V and a 440 V switchboard and an associated Secondary Electrical Control Panel controlling the Air Circuit Breakers located in the two main switchboard rooms on No. 2 Deck. The SECPs serve two functions: they provide a reversionary control and maintenance position for their own sub-system, and they house the centralized and dedicated control and protection facilities associated with the sub-section utilizing the D86 computer-based Control and Data collection unit.

The switchboards also house a 440 V Moulded Case Circuit Breaker (MCCB) distribution section and three Mk.121 VR Automatic Voltage Regulators, one for each DG and one for the MG associated with the sub-system.

Three-Position Diesel Output Selection Switch (3-Position Switch)

A control is provided on the supervisors' desk in the SCC which allows control of the maximum power that the Propulsion motor can draw as a function of DG loading. The switch is known colloquially as the three-position switch and has the following settings:

(*a*) 85%—The normal position designed to limit DG load to the preferred level for maximum DG life between overhauls.

(*b*) 100%—This position would be used when a higher state of readiness is required to give more available power.

(*c*) 110%—This position is used in emergency, giving the overload capacity of the DGs to the system. This switch position automatically initiates the load shedding procedure on the 440 V system, which in turn allows more power to be made available for propulsion motor use.

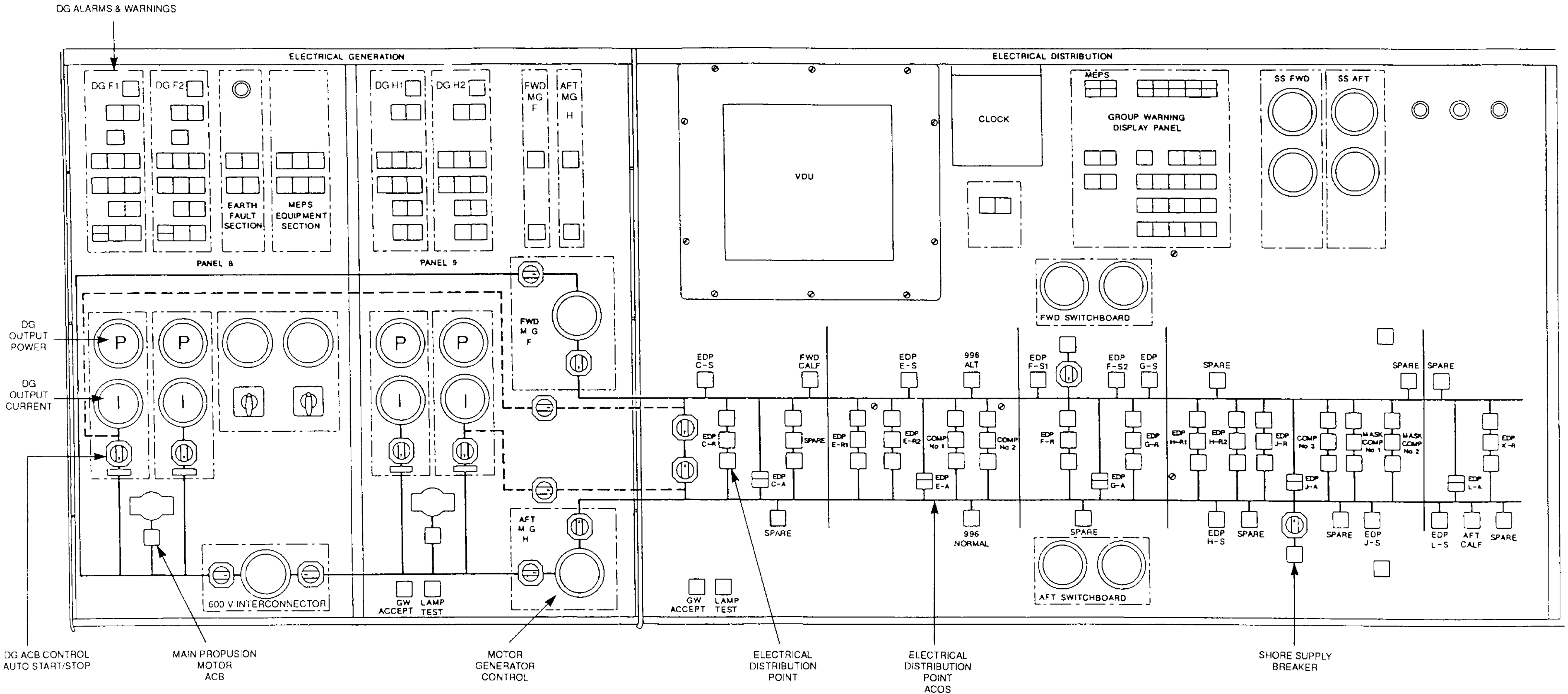

Fig. 2—Primary Electrical Control Panel: controls and indications

ACB: Air Circuit Breaker
ACOS: Automatic Change-Over Switch
CALF: Calorifier
DG: Diesel Generator
EDP: Electrical Distribution Point
EM: Propulsion Motor
GW: Group Warning
I: output current
MEPS: Main Electrical Propulsion System
MG: Motor Generator
P: output Power
ROCOS: Remotely Operated Change-Over Switch
VDU: Visual Display Unit

It should be noted that the stopping capability of the ship is largely dependent upon regeneration of energy from the propulsion motors via the thyristor convertors and MG sets into the ship's load. The initiation of load shed therefore can have an adverse effect on the ship stopping distance by reducing ships load. The use of this switch will depend very much on the discretion of the operator and the ship scenario.

Diesel Generator Overload Protection

If a combined propulsion and ship's load greater than the power available were to be connected to the system then the generators would become overloaded. Two methods are employed to prevent this occurring:

(*a*) Propulsion power is limited to the power available. (It was a design decision to give priority to the 440 V ship's systems.)

(*b*) The shedding of non-essential 440 V loads.

The first of these two methods is a propulsion regulator function and will be described in a later section. The second is a MEPS function and a load shed is initiated under any of the following circumstances:

(*a*) by operator signal via a push button on the SCC operators' console;

(*b*) when the DG load selection switch is set to 110%;

(*c*) when the output power of any DG or MG set exceeds a preset level;

(*d*) when the output current of any DG exceeds a preset level.

The system philosophy is such that 440 V loads should always take preference over propulsion motor load. In the event of the tripping of the designated non-essential loads the 440 V system load would be reduced by approximately 350 kW.

Provision of Normal, Alternative and Sheddable Loads

The distribution system in the Type 23 has diverged considerably from recent RN practice and this is particularly so in the provision of normal and alternative supplies to equipments.

The principles of the 440 V distribution system are shown diagramatically in FIG. 3. The distribution sections of each main switchboard contain 30 MCCBs most of which supply either Automatic Change-Over Switches (ACOS), Remotely Operated Change-Over Switches (ROCOS) or sheddable load MCCB assemblies. The priority of maintaining a supply to a particular system or piece of equipment determines whether it is connected to either an ACOS or ROCOS fed supply or is designated as a non-essential load and has the facility to be shed from the system. In the event of loss of power to a 440 V switchboard, e.g. by MG set failure, an ACOS will maintain supplies to those equipments fed from it. Correspondingly, ROCOS supplies can be restored manually, by the operator in the SCC, subject to the availability of power.

A few high value equipments (e.g. steering motors) are fed with normal and alternative supplies (each provided from an ACOS) via an adjacent Hand Change-Over Switch (HCOS) and fed from different Electrical Distribution Points. The integrity of supplies to these equipments is correspondingly greater.

A number of Static Frequency Changes (SFCs) are fed with 'no break' supplies. These are supplied with power from both switchboard sources via MCCBs simultaneously. In the event of one supply failing, then there is a corresponding increase in power taken from the other switchboard.

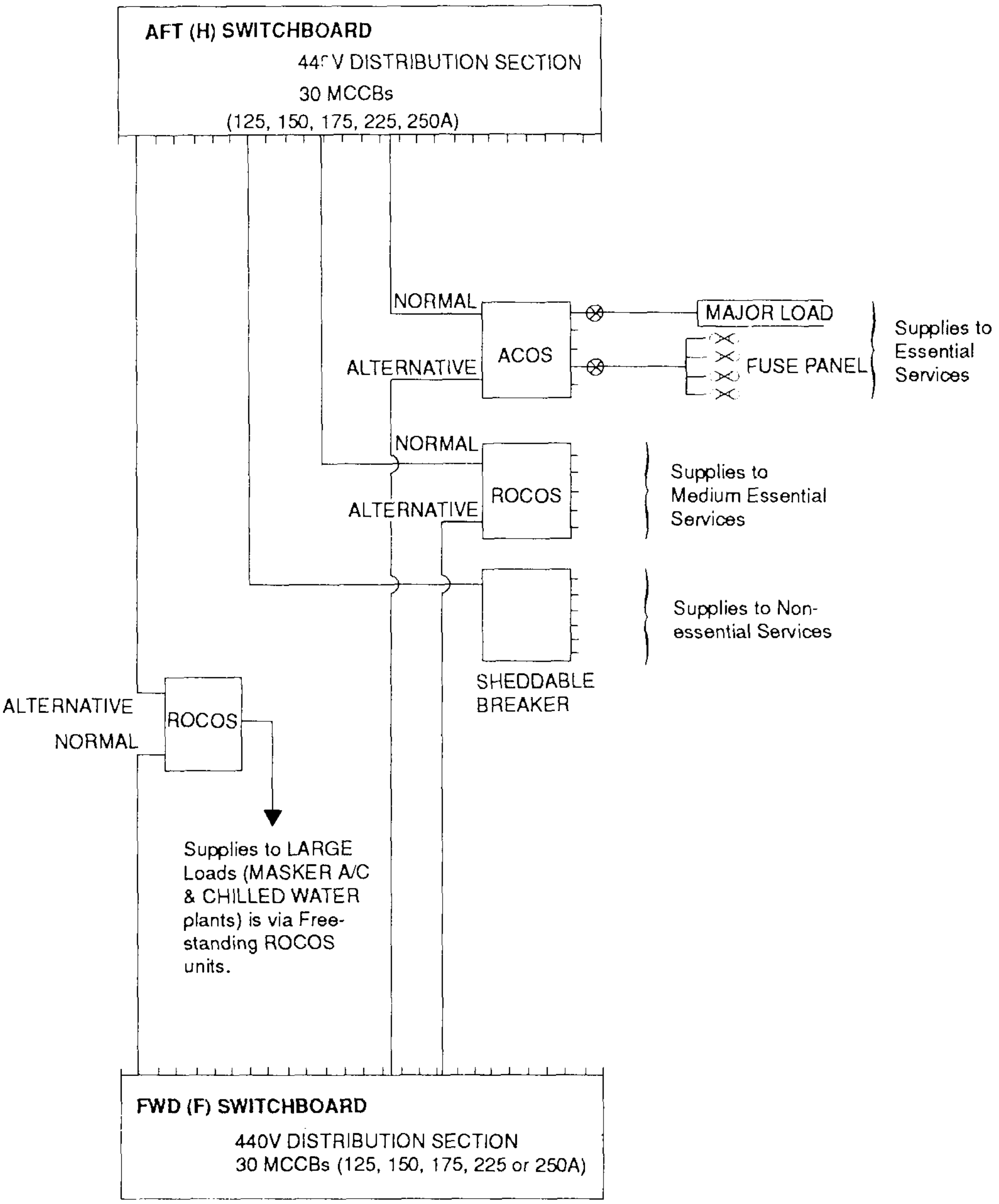

FIG. 3—THE PRINCIPLES OF THE 440 V DISTRIBUTION SYSTEM

ACOS: Automatic Change-Over Switch
MCCB: Moulded Case Circuit Breaker
ROCOS: Remotely Operated Change-Over Switch

One feature of the ship is the reduction of Electrical Distribution Centres EDC), as has become common in other recent designs of RN ships. With he exception of the two electrical distribution centres co-located with the nain switchboards, the remaining ACOSs and ROCOSs are situated at Electrical Distribution Points the majority of which are in passageways and obbies on 2 Deck. An EDP (EDP) may consist of as little as one change-ver switch and its associated MCCBs. The general principle of one change-ver switch feeding several services has enabled a reduction in the number f automatic and remote change-over switches required. There are only six COSs in the ship, one in each of the five fire zones plus a dedicated unit or the 996 radar supply. A total of nine ROCOSs feed EDPs and five free-tanding ROCOS units which feed the large electrical loads of the two Masker ir Compressors and the three Chilled Water Plants.

ELECTRIC PROPULSION SYSTEM

Each shaft set of the electrical propulsion system consists of two major components, a combined propulsion regulator converter and a 1·5 MW 750 V d.c. electric motor. The function of the propulsion regulator and thyristor converter unit is to supply variable direct current power, rectified from the ship's 600 V a.c. system, to the electric motor armature and field circuits to give optimum performance and protection of the electric motor throughout the propeller speed range. The rectification is performed by heavy duty thyristors controlled by a regulator assembly which processes the

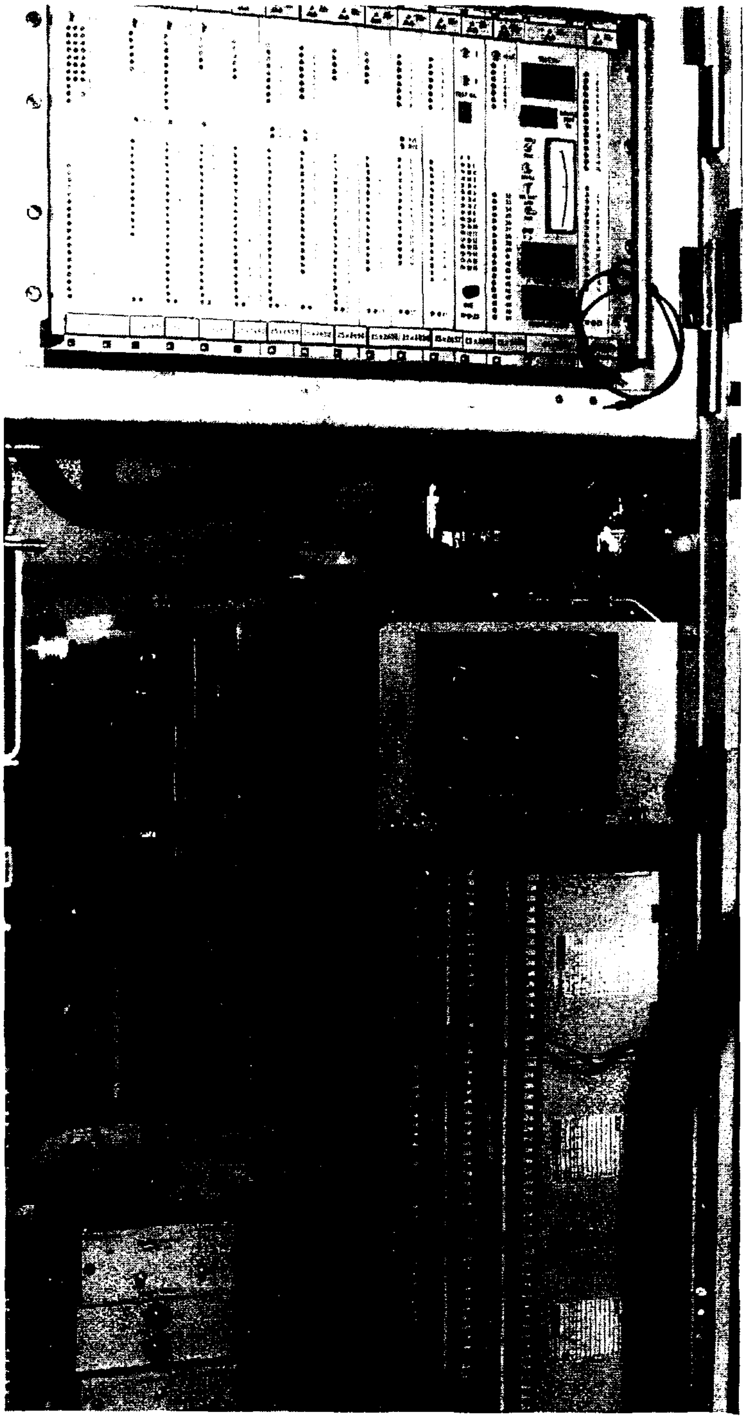

FIG. 4—PROPULSION MOTOR REGULATOR AT THE TOP OF THE FIELD CUBICLE IN THE CONVERTER ENCLOSURE

manoeuvring demand signals. Reversal of the motor direction is performed by field reversal while maintaining the direction of the armature current. Two regulator converter units are fitted to the ship, each providing a dedicated d.c. drive to its related propulsion motor. The regulator, which is the heart of the electric propulsion system, comprises analogue electronic circuits contained on 15 plug in modules which fit into a 19 inch heavy duty sub-rack. The rack is mounted in the field cubicle of the converter enclosure which is situated behind the local motor control position as shown in FIGS. 4 and 5.

Normal control of the regulator/converter and hence motor is by movement of the Power Demand Levers (PDL) situated in the SCC. Bridge control is not fitted, although proposed for later ships. Two reversionary controls are available at the regulator panel: Rev 1 which allows local control of the electric motors with all the regulator protection circuits operating, and Rev 2 control which allows control of the motor locally but with only limited protection. Rev 2 control is therefore only used in emergency in the event of partial regulator failure.

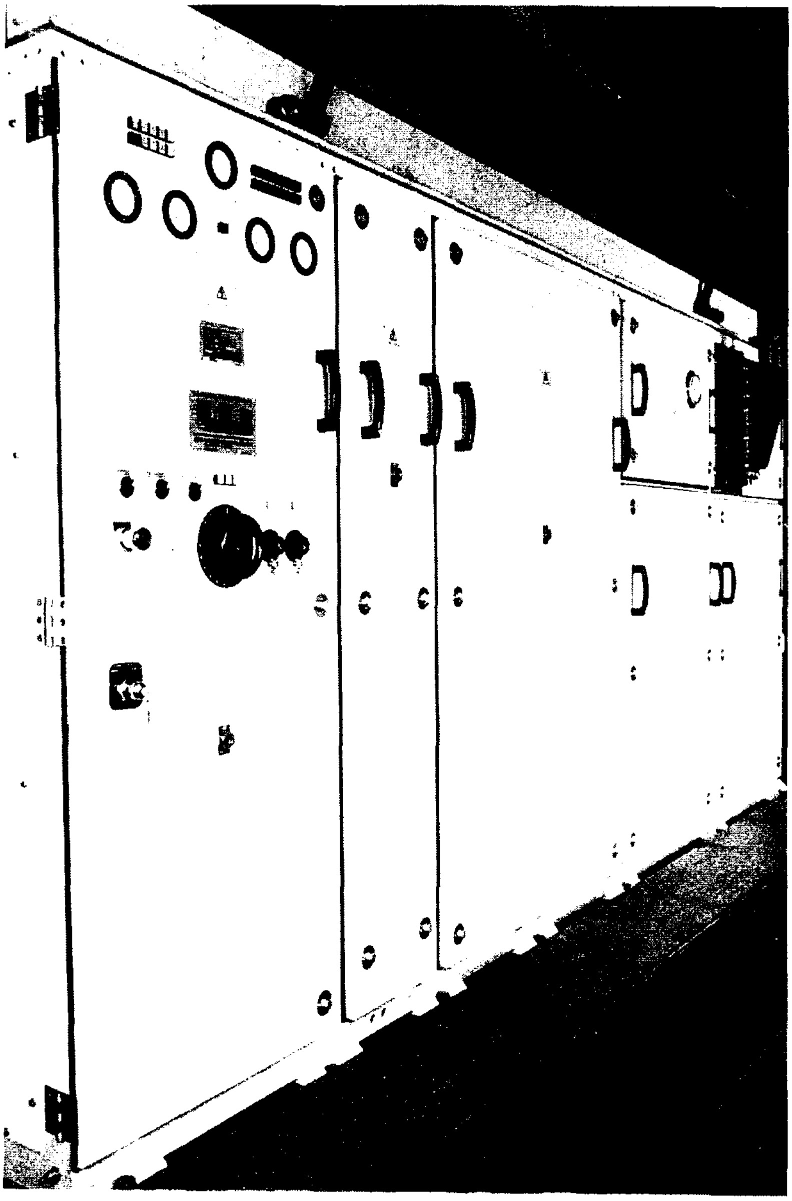

FIG. 5—THE REGULATOR AND CONVERTER UNIT, SHOWING THE LOCAL CONTROL PANEL IN THE FOREGROUND

The primary regulator functions can be divided into three areas:

(*a*) Control of armature current.
(*b*) Control of field current.
(*c*) Power available computation.

These will be described briefly in the following sections.

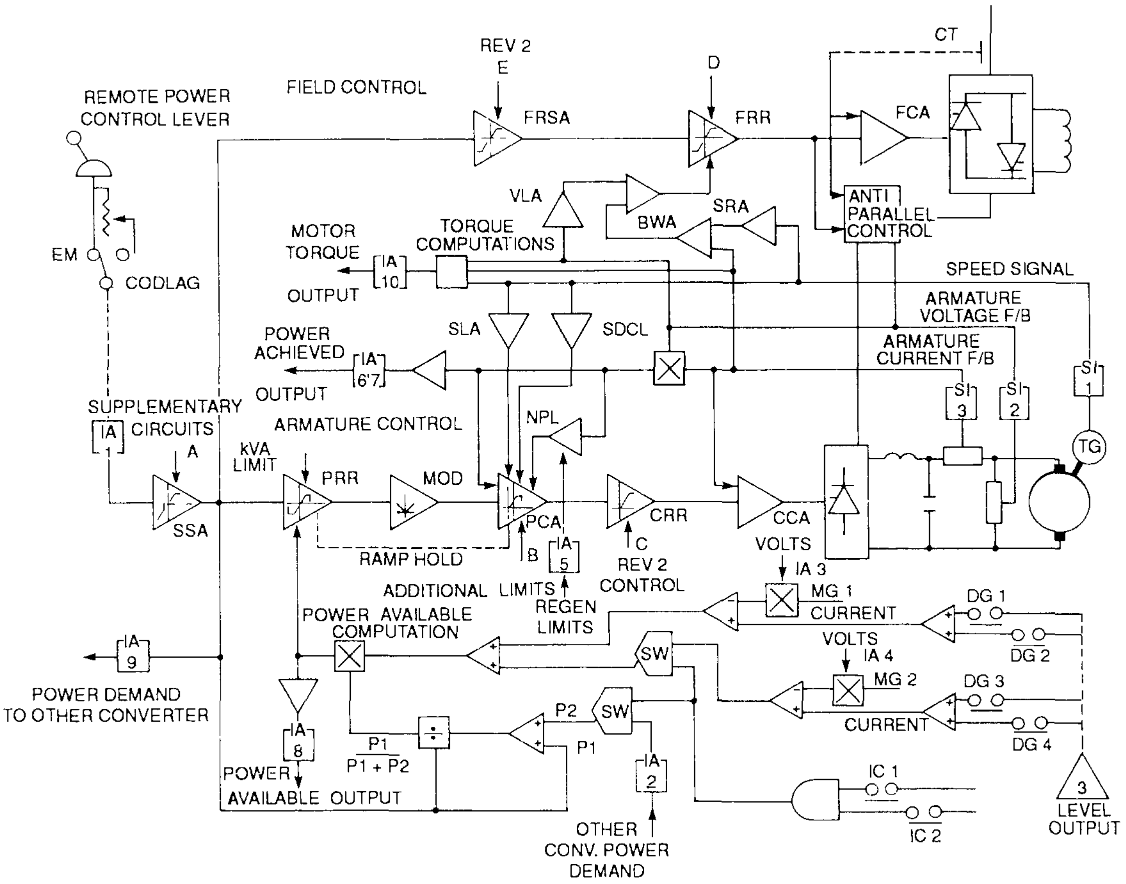

FIG. 6—PROPULSION MOTOR REGULATOR

BWA:	Brush Wetting Amplifier
CCA:	Current Control Amplifier
CRR:	Current Reference Ramp amplifier
CT:	Current Transformer
DG:	Air Circuit Breaker for Diesel Generator
EM:	Propulsion Motor
F/B:	feedback
FCA:	Field Control Amplifier
FRR:	Field Reference Ramp amplifier
FRSA:	Field Reference signal Shaping Amplifier
IA:	Isolating Amplifier
IC:	Air circuit breaker associated with 600 V interconnector
MG:	Air Circuit Breaker for Motor Generator
MOD:	Modulus Amplifier
NPL:	Negative Power (regenerative) Limit amplifier
PCA:	Power Control Amplifier
PRR:	Power Reference Ramp amplifier
SDCL:	Speed Dependent Current Limit amplifier
SI:	high accuracy Signal Isolating amplifier
SLA:	Speed Limiting Amplifier
SRA:	Speed Reference Amplifier
SSA:	Signal Shaping Amplifier
SW:	switch
TG:	tachogenerator
VLA:	Voltage Limit Amplifier

Armature Control Loop

The PDLs produce a 4 to 20 mA signal which is scaled proportionally to the major power demand from full ahead to full astern. This signal is passed through an isolating amplifier and is then linearly converted to give a −10/0/10 V signal output from the Signal Shaping Amplifier (SSA) (see FIG. 6).

An incoming signal between 11 and 13 mA represents a zero power demand. The minimum non-zero output from the SSA, corresponding approximately to the 11–13 mA deadband input, is 0·25 V. This voltage corresponds to 40 kW motor output power, producing a minimum shaft rotation of about 25 rev/min.

Several supplementary circuits are input to the SSA at Input A. These include:

(*a*) A sample/hold circuit which applies a fail set signal to the SSA if the incoming signal from the PDL deviates from the 4–20 mA range.

(*b*) A null detector which detects zero power demand and which has to be initiated before the main converter ACB can be closed.

(*c*) A both-fan loss circuit limits the motor power output to 125 kW in the event of both motor cooling fans failing.

(*d*) Rev 1 control which can be switched in to replace the remote power signal.

The Power Reference Ramp amplifier (PRR) converts rapidly changing signals within the SSA to a rate of change of propulsion motor power which is acceptable to the diesel generation power supply system. In addition there are two limit circuits which interrupt the ramp output:

(*a*) *The kVA limit circuit* which interrupts the input to the ramp amplifier when the current limit of any DG supply breaker or 600 V interconnector breaker is reached. This signal is derived directly from the D86 controlled MEPS protection system.

(*b*) *The power available circuitry*, which is described later, limits the power consumption of the main propulsion electric motor (EM) to the system capability. A sudden reduction in power available, for example caused by a DG failure, will rapidly reduce the power consumption of the motor to the reduced system capability. An increase in the available power will only take place at the PRR ramp rate. A further feature of the PRR is the ramp hold which is initiated by the various current limit circuits acting on the power control amplifier.

The power signal is then passed from the PRR through the modulus function to change it to a uni-directional value for ahead and astern demand. The signal is then converted into the armature current reference by comparison with the power achieved signal in the Power Control Amplifer (PCA). EM Power achieved is derived by multiplying current and voltage as seen at the motor armature terminals.

The PCA contains a number of important limit circuits, incorporated for the following reasons:

(*a*) *Speed Dependent Current Limit (SDCL).* When in CODLAG mode at shaft speeds greater than 164 rev/min, the current reference is progressively reduced so that armature current reduces from 100% at 164 rev/min to approximately 85% at 190 rev/min. The speed signal is derived from the shaft tachogenerator and is shaped in the SDCL Amplifier. This limit is necessary to overcome possible commutation difficulties of full load current at high shaft speeds and also the danger of flash over.

(*b*) *Overspeed Limit (OSL).* This circuit also operates from the tachogenerator signal via the Speed Limit Amplifier and reduces the current signal to zero when the shaft speed reaches 200 rev/min.

(*c*) *Regeneration Capacity.* During manoeuvring, for example from ahead to astern, the direction of the EM field current is reversed. During this transient and until the shaft stops, the motor effectively becomes a generator being driven by the propeller. The electrical energy produced is fed via the thyristor converter and MG sets into the ships 440 V load. This is known as regenerative braking and the amount of regenerative power produced has to be limited to the level which can be absorbed by the ship's load. The level is normally controlled automatically by a signal from MEPS and is set to 75% of MG set load. When operating with the 600 V interconnector breakers closed, each motor is controlled so that its maximum power regeneration is equal to half 75% of the total input power of the two MG sets. This signal acts on the PCA in the regeneration mode only to limit the current demand signal as necessary.

A number of additional limit circuits operate at Input B to the PCA, including:

(*a*) Limiting of EM power in the event of 1 cooling fan failure.

(*b*) Under frequency circuit. If the 600 V system frequency falls to 58·5 Hz, then the current demand signal is reduced to maintain this level.

(*c*) Over frequency circuit. This operates in the regeneration mode only. Armature current is reduced if the 600 V system frequency rises to 63 Hz.

When these limits are exceeded a fast acting/slow recovery circuit controls the situation. Therefore, in the event of a limit being exceeded, the current reference signal is reduced rapidly to the necessary level at the Current Reference Ramp Amplifier rate. When the limiting condition is removed, the current reference signal returns to normal at the slower PRR ramp rate.

The current reference signal now passes to the current reference ramp (CRR) amplifier which provides an ultimate limit on the rate of rise or fall of current demand signal. In general the much slower signal ramp rate applied at the PRR will override the CRR ramp.

Two important features are Input at the CRR amplifier. Firstly 'Rev 2' control allows local control of the Thyristor Converter by the handwheel with the preceding regulator circuit functions by-passed. Secondly the brush wetting currents are initiated at this point. Brush wetting is a feature which has been included to operate when EM power demand is low and the shaft is being driven either by the gas turbine alone or in CODLAG with low EM bias set. This operates at speeds greater than about 53 shaft rev/min. The action is to apply a set reference to the CRR to establish a current flow through the armature. This current flowing through the brushes and armature of the motor helps to prevent brush glazing problems which might otherwise occur.

Finally, the 0–10 V signal from the CRR is compared with the circuit feedback signal in the Current Control Amplifier (CCA) to produce the basic phase shifting signal for the armature converter. This then produces the voltage signal required to operate the firing circuits for the thyristor converter.

Field Control Loop

The second major part of the regulator is the motor field control loop. In normal operation the field control signal is derived from the output of the signal shaping amplifier (SSA) in the main armature control circuit. This signal is then shaped in the Field Reference Shaping Amplifier (FRSA). Field current shaping is designed to give 36·0 amps below 250 kW power demand and 42·5 amps above 250 kW power demand. The field demand signal is then passed to a ramp amplifier, the field reference ramp amplifier (FRR), to limit the rate of change of field current. The action of this ramp rate amplifier is similar to the PRR in the armature current control loop. The FRR also has the effect of controlling the rate at which field current reversal (e.g. for regenerative braking) can take place; full field reversal is set to take about 14 seconds. Several limit circuits act at input D to the FRR:

(*a*) *Brush Wetting Amplifier.* This circuit ensures that sufficient current flows in the armature circuit for Brush Wetting purposes. It is effective for speeds above 53 rev/min (CODLAG drive) and its action is to reduce the field reference signal thus weakening the field current and thereby increasing the armature current to a sufficient level to prevent commutation difficulties.

(*b*) *The Voltage Limit Amplifier (VLA).* Under CODLAG operation as the shaft speed rises above the EM maximum level of 88 rev/min the armature voltage will tend to rise above its normal maximum of 750 V. This circuit progressively weakens the field current as shaft speed increases to limit the armature terminal voltage to 750 V.

In the regeneration mode the VLA acts in a similar way except that the negative voltage limit is set to 450 V to give a satisfactory margin on inversion.

Input D to the FRR also has two field boost circuits which operate under the following conditions:

(*a*) *Single Diesel Generator Circuit.* This is operational when a propulsion motor is being supplied from one DG only and the interconnector is closed. In this situation the field current is boosted to full value for low power demand signals to the regulator. This enables the converter to operate at a higher voltage for this condition, thus reducing the kVAR (kilovolt amps reactive) demand on the generator which could otherwise be excessive when combined with the MG set load.

(*b*) *Stall Boost Circuit.* A shaft stall condition is deemed to exist if this circuit sees a speed feedback signal of less than 5 rev/min, an armature voltage feedback signal below 60 V, and current feedback signal above 800 amps. In this case the circuit boosts the field reference signal to the full field condition to provide increased breakaway torque. Associated with this action a converter ACB trip signal is produced after a delay of 20 seconds, if the stall condition persists, to safeguard the motor.

The −10/0/10 volt signal from the FRR is compared with the field current feedback signal in the Field Control Amplifier (FCA) to produce the phase shifting signal in the field converter.

The field converter consists of two bridges connected to give opposite polarity outputs, with one bridge suppressed at any given time; the anti-parallel logic operates so as to place an inhibit on the opposite polarity bridge. When field reversal is demanded no change to the operating bridge is allowed until the zero current detector indicates zero field current. At this point the inhibit is applied to the bridge which has just been operating and after a delay of 12 milliseconds, to ensure the field current remains at zero, the inhibit on the opposite bridge is lifted to allow conduction of field current in the new direction. With a zero field current demand both inhibits are on. A phase shift amplifier conditions the phase shift signal from the FCA to produce a positive going signal, for either direction of field current to suit the firing circuits.

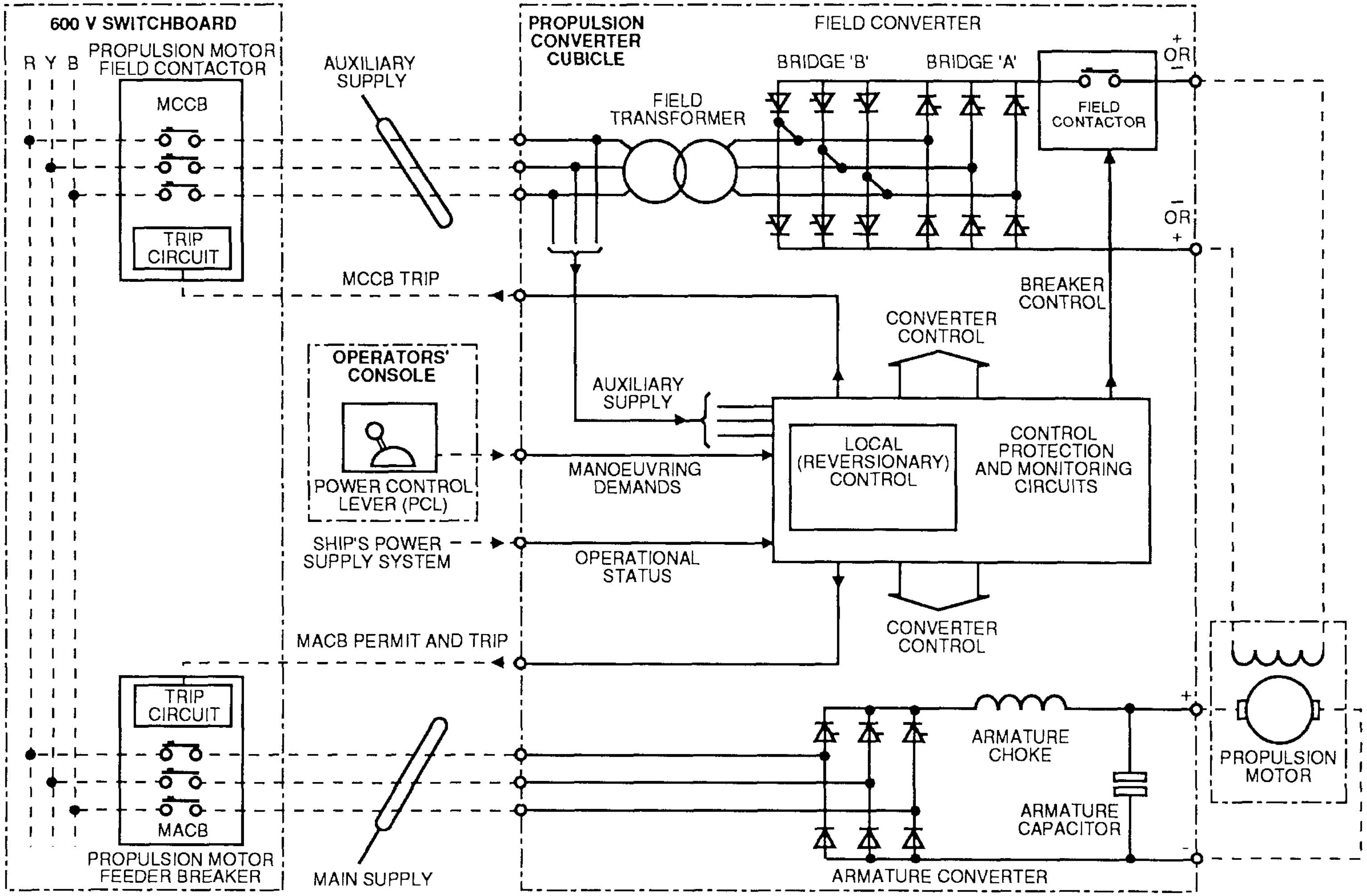

Fig. 7—Main operational features of the Electrical Propulsion System

Power Available Computation

To comply with the design requirement to give the ship's 440 V load priority of supply, power available to the propulsion motors is limited to the balance of power remaining after allowing for losses and subtracting the ships load.

The basic inputs to the power available computation are digital/relay signals from the diesel generator and interconnector ACBs, analogue MG input currents, and signals from the three-position DG load selection switch. If at least one of the 600 V interconnector ACBs is open then the power available for the propulsion motor is computed from its own sub-system only using the following algorithm.

$$\begin{bmatrix}\text{Total Sub System}\\ \text{Power Available}\end{bmatrix} = \begin{matrix}\text{(No. of DGs running} \times \text{3-position switch}\\ \text{setting} \times 1{\cdot}3\text{ MW)} - \text{(MG Set input}\\ \text{power} + 80\text{ kW)}\end{matrix}$$

(The 3-position switch in the SCC on the supervisors' desk may be set to 85, 100 or 110%).

The extra 80 kW subtracted per motor is to allow for loads such as the motor and converter cooling fans and the motor field circuit power which are all supplied directly from the 600 V system and are therefore not seen at the MG input.

If both interconnector ACBs are closed, the two sub-systems net powers are added and then proportioned according to the power demand of each propulsion motor system, i.e.:

$$\left[\frac{\text{PD1}}{(\text{PD1}+\text{PD2})}\right] \times \begin{bmatrix}\text{Total System Power}\\ \text{Available}\end{bmatrix} = \begin{bmatrix}\text{Actual Power Demand}\\ \text{Limit 1}\end{bmatrix}$$

For this computation a power demand input signal is required from the other converter and likewise the power demand signal for this converter must be output to the other one. Both these signals are transmitted as milliamp signals and are passed through isolating amplifiers.

The power available signal is then fed into the PRR as a limit as described earlier. When the power available limit is reached a warning is indicated in the SCC.

Converter

The regulator system covers the total control scheme but excludes the thyristor firing circuits which are a converter function.

From the shaped field and armature demand signals, the regulator generates two separate phase-shifting reference signals which are transmitted to the converter field and armature firing circuits respectively. In each case the reference signal is compared with a ramp signal generated from each phase of the reference voltage from the primary power supply. A trigger pulse is produced at the point of cross over in each phase and causes a burst of firing pulses to be generated which lasts until the end of the conducting cycle of the respective pair of thyristors. The main operational features of the propulsion converter are shown in FIG. 7. The field and armature power are then fed to the reversing d.c. motor which is mounted in the shaft line aft of the gear box. An armature choke and capacitor are fitted to reduce electrical distortion which might otherwise produce underwater radiated noise transmitted via the electric motor seating to the hull.

CONCLUSION

As with any new system, teething problems were experienced during the set-to-work and the trials period of the Type 23 electrical propulsion and distribution systems. In general though these have been confined to fine tuning, and the electrical systems have proved reliable, flexible and easy to operate.

It is noteworthy that there was no increase in motor size or installed generating capacity incorporated to reflect the ship's growth during design from 100 m to 123 m in length. Nevertheless at full power on electric drive the ship speed meets the Staff Target and early indications are that the noise signature of the ship is below the target level.

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