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The practical application of modern simulation tools throughout the design and trials of a diesel electric propulsion system

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This paper describes the application of modern simulation tools in the design, setting-to-work, commissioning and operation of major shipboard systems. To illustrate the techniques used, a full Diesel Electrical Propulsion System is used as the case study, tracing the evolution from conceptual design through to service operation, analysis of trials results and final model validation. Past experience with simulation and the efficiency of modern tools enabled a variety of innovative features to be tested at the design stage, and to be adopted with confidence in the chosen system configuration. Simulation results and trials results are presented, with a particular focus on harmonic control, power management performance and transient stability of the system. An example of simulation as a through-life vessel support tool is presented, demonstrating the development, installation and validation of system enhancements in response to specific owner requirements.

BACKGROUND

In November 1991, the authors' company was awarded a contract by Ferguson Shipbuilders to design and supply a full Diesel Electric Propulsion System for a 2000t Lighthouse and Buoy Tender Vessel. The vessel, MV *Pharos*, is now in service in Scottish waters with the Northern Lighthouse Board, having been handed over on 6th May 1993.

Based on their experience with naval propulsion and electrical power and control systems, the authors' company produced a system incorporating significant innovation. The use of modern simulation tools was essential in order to achieve the necessary level of confidence in the design, and to deliver a fully working system within short timescales.

INTRODUCTION

The design process for naval vessel propulsion systems has frequently used simulation techniques for two decades. The demand arose from the requirements of automatic remote control, the application of gas turbines and cp propellers with their associated torque/speed interactions, and the prospect of improved manoeuvrability with these configurations. In parallel with such marine engineering developments, computing power rose dramatically from the analogue machines used in the 1970s, through hybrid, to the digital power of today.

Modern simulation tools have transformed the simulation task from a mixed application engineering/computing technology effort into an almost entirely applications oriented task. The computing technology has become virtually transparent.

The target application chosen to illustrate this point is a ship's diesel electric propulsion system. In simulation terms it is a high bandwidth system, with significant time constants ranging from a few milliseconds to several minutes. The system elements are highly interactive and the particular project demanded some significant control system development. Additionally, such systems can be time consuming to commission and an accurate design simulation was seen as potentially reducing tuning and sea trials time.

Authors' biographies

P Sallabank joined Vosper Thornycroft Shipbuilding Division in 1971 as an electrical engineer working on naval vessel power system design, machinery control and instrumentation. In 1975 he joined the Controls Division team engaged in the development of propulsion system and power system simulation. From 1991 to mid-1994 he was manager of the Marine Systems Department taking responsibility for commercial marine electrical and control systems, including that for the Northern Lighthouse Board vessel MV *Pharos*. He has recently transferred to the Support Projects Division where he is involved in market testing.

A Whitehead graduated from Imperial College, London, in 1985 with a BEng in Electrical Engineering. He continued in employment with his sponsoring organisation, GEC Traction, and was responsible for the electrical design, manufacture and commissioning of the British Railways' Class 91 140 mph locomotive. He moved to Vosper Thornycroft Controls in 1991 as Principal Electrical Engineer and was responsible for the electrical system design, specification, procurement and commissioning of the diesel electric propulsion system on MV *Pharos*.

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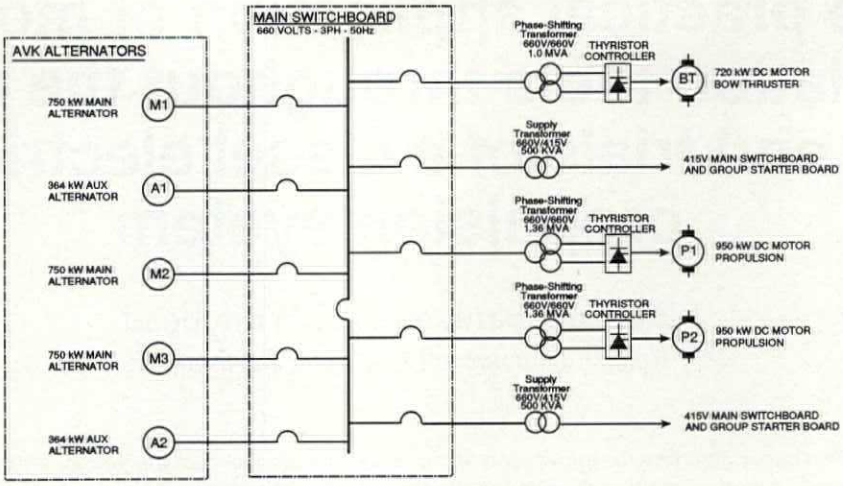

Fig 1 Power generation single-line diagram

This paper outlines both the system studied and the simulation tools used. Aspects of design where simulation has had the greatest impact are addressed in some detail.

Actual trials results are presented and a comparison with simulation results is discussed. The importance of good trials recording cannot be over-stressed. Without it, the quality and accuracy of simulation models cannot be measured and, most certainly, cannot be improved.

Programme timescales are given and discussed. Whilst not of scientific interest, they do provide an insight into the speed with which complex models can now be built, and also show the benefit to overall project timescales in terms of reduced tuning and trials time.

The experiences of 18 months in-service operation are discussed, providing an example of the application of simulation as a through-life support tool to vessel and owner.

CASE STUDY SYSTEM

In order to demonstrate the simulation work done, it is necessary to outline the system to be simulated and the particular areas of design requiring detailed study.

The diesel electric propulsion system to be studied is for a Lighthouse and Buoy Tender Vessel. This is a multi-role all-weather vessel required to carry out both routine and emergency tasks around the Northern UK coast. Typical operations include replenishment, hydrographic survey, buoy handling, towing, wreck location and helicopter operations. The requirement is therefore for a high integrity system giving good manoeuvrability, hovering capability, and good fuel economy across several different operational modes and speeds.

Preliminary design work established the basic configuration shown in Fig 1.

Key design tasks

The key design tasks that either necessitated simulation or would benefit from simulation were identified as follows:

Ship/propulsion performance

1. steady state powering and vessel performance;
2. manoeuvring (for different ship operating modes and various system configurations);
3. failure modes.

Electrical power system

1. quality of power supplies;
2. load flow analysis;
3. fault level;
4. transient response;
5. harmonic penetration;
6. supply system/load interaction;
7. protection co-ordination;
8. failure modes;
9. operating efficiency and power factor.

Control systems

1. power management;
2. shaft speed control;
3. failure modes.

Simulation output requirements

The required output of these simulation based design tasks is as follows:

Ship/propulsion performance – steady state

Against a base of ship's speed in various hull states and system configurations, the following are required:

1. shaft/motor speed;
2. shaft/motor torque;
3. motor input power;
4. converter output power;
5. converter input kVA, kW, kVAR, power factor;
6. efficiency.

Ship/propulsion performance – manoeuvring

Plots of ship, machinery and electrical system parameters for a range of ship manoeuvres are required. These manoeuvres include both classical crash stop and slam accelerations, as well as slow speed manoeuvring, hovering, and unusual or abnormal configurations such as single shaft operation.

The output plots provide information enabling control development to improve manoeuvrability, ensure machinery remains within safe limits, and prove security of power supply, particularly under various failure modes.

Electrical power system

1. The quality of power supplies determination to provide a common specification to all suppliers of electrical equipment on the vessel.
2. The load flow under different operating modes and configurations to determine voltage drops, and to validate cable ratings; also to identify Power Management System (PMS) switching thresholds and governor and Automatic Voltage Regulator (AVR) droop settings.
3. Making/breaking fault currents at different points in the distribution network to enable correct and economic selection of circuit breakers and protection devices.
4. The transient response of system to motor starts, transformer magnetisation and faults such as generator trips. Resultant determination of machine reactances, governor and AVR gains and control loop stability to ensure compliance with specified performance and Lloyd's Register requirements.
5. Harmonic penetration, resulting from thyristor converter harmonic currents under different configurations and loads, to determine machine reactances and identify prospective power system resonances.
6. Supply system/load interaction to establish any load control requirements to prevent propulsion demand overloading connected generator capacity.
7. Protection co-ordination to determine circuit breaker short time and long time trip settings and discrimination proved under all valid configurations.
8. System tolerance of failures is particularly important in a diesel electric ship due to the potential for blackout and consequent threat to ship safety. Output in this study area covers the results of control failures, as well as power system failures, including diesel generator trips.
9. Operating efficiency and power factor under transient and steady state operating conditions to validate generator selection and determine the need, or otherwise, for power factor correction equipment.

Control system

The studies identified above create a database and knowledge of inherent system performance characteristics from which the intended control strategy can be both tested and developed in detail.

1. PMS studies enable the control logic, switching thresholds, generator loading/unloading rates and tuning margins to be established and proved throughout the range of operating modes.
2. Shaft speed control encompasses all the logic associated with bridge and machinery control room lever control of propulsion. Motor control loop (current, speed and power) settings are established and the interactive protection system executed by the motor control and PMS is demonstrated.
3. Demonstration of satisfactory failure modes is on the full system, to prove acceptable performance of control in response to machinery failure as well as control failure.

SIMULATION REQUIREMENT

Having specified the simulation tasks and required outputs, the simulation tools and techniques can be established. An additional requirement was imposed on the simulation technique decision process – that being a requirement for a structured approach that would allow each equipment model to be run and tested in isolation from the system. This requirement enables model validation work to take place throughout the project life-cycle, from basic equipment design to final acceptance trials.

Whilst this object oriented approach may seem obvious, it can be practically difficult to implement. For example, a distributed control system philosophy may be adopted but the downstream design process can only resolve the optimum location for some functions. If failure mode analysis is to be conducted properly using simulation, this approach needs to be strictly followed. The by-product of this approach is that models of individual equipments enable the 'building block' approach when building a system model of a different configuration.

THE SIMULATION TOOLS

Past experience in building single, whole system models of complex propulsion systems has indicated a number of problems. These models are time-consuming to build, inefficient to run in terms of run time, and only one study can be conducted at any one time. For this project, which had a short timescale, the power system and propulsion system needed to be studied in parallel.

Two major models were therefore defined:

1. a power system model;
2. a propulsion system model.

Due to the interactive nature of the overall system, the propulsion system model would incorporate a limited power system model and the control models.

Power system model

Interactive Power System Analysis (IPSA)[1] was an automatic choice for this model, as it provided the full range of electrical analysis facilities required for the project. This analysis package had been used successfully on other projects, including a number for the MOD(N) whose preferred electrical analysis platform is IPSA.

The IPSA package is fully validated and used extensively in the power generation and offshore industries, as well as by a number of major UK electrical consultancy companies. Validation by others, in addition to that carried out in-house, provides a high level of confidence in results and designs obtained through the application of IPSA.

Propulsion system model

MATLAB-SIMULINK[2] was used as the base analysis package for this model since it provided the necessary facilities for an efficient and structured model build, with high level instructions and self-documentation. It provided a suitable environment for control system development, this being particularly important given that an innovative approach to some aspects of control – in particular the PMS – was planned.

MATLAB-SIMULINK has been successfully applied by the authors' company to a broad cross section of marine simulation activities, including detailed PMS design, ship position control systems and cp propeller pitch control systems. A library of generic models for the primary elements of propulsion systems are maintained, providing a quick model build capability, as well as a proven detailed analysis platform. Future developments of this, and other equivalent packages, will permit automatic generation of application software from the model, and the ability to run simulations in true real-time with wide ranging possibilities for operator training.

Supporting facilities

A number of supporting analysis tools are also used:

Steady state analysis

Spreadsheet analysis of steady state powering in different modes is undertaken. This is particularly useful in propulsion systems where, for operational reasons, intermediate points on the power/speed curve need to be optimised. Also, given the range of different generator combinations, deck machinery loads and general ship services loads, a spreadsheet is the most efficient method of calculating all possible conditions.

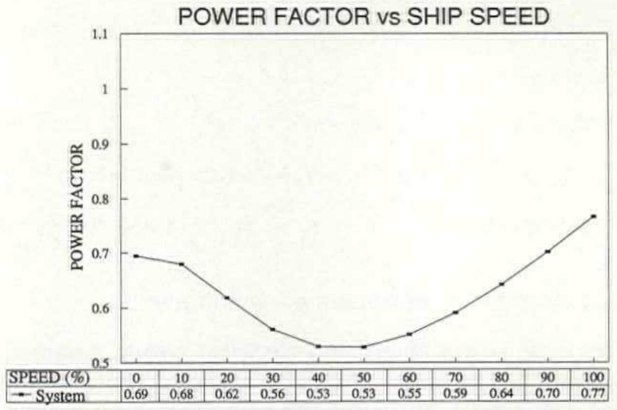

Fig 2a Steady system power factor; system power factor without correction

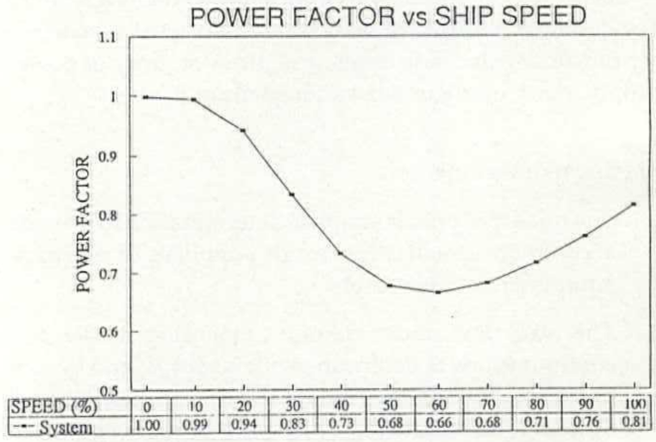

Fig 2b Steady system power factor; system power factor with correction

Data testing

Complex, interactive models demand a complex range of data and create a difficult environment for diagnosing data errors, particularly for the less significant data elements. To overcome this, data testing prior to loading into the full model is necessary.

Data format can also present a problem. For example, electrical machine data may be supplied as design values, or test results or a mix of both.

To resolve these problems a number of spreadsheet models have been developed, which test machine data by creating terminal performance characteristics from design data, and test the sensitivity of the terminal performance to each data element.

Trials recording

Trials recording is an important aspect of simulation, as it provides the ultimate validation – or otherwise – of the modelling work done. A Personal Computer (PC) based

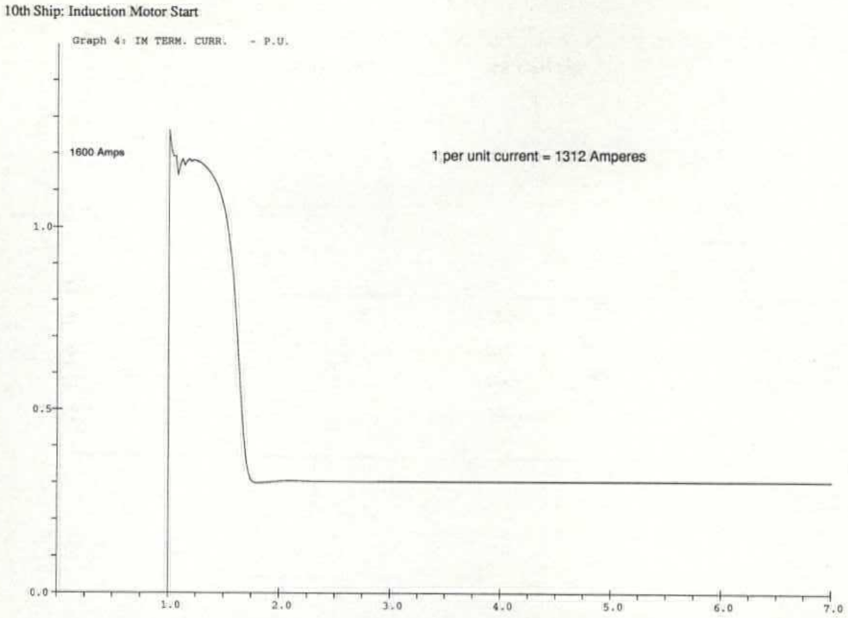

Fig 3a Induction motor data testing; simulated induction motor start

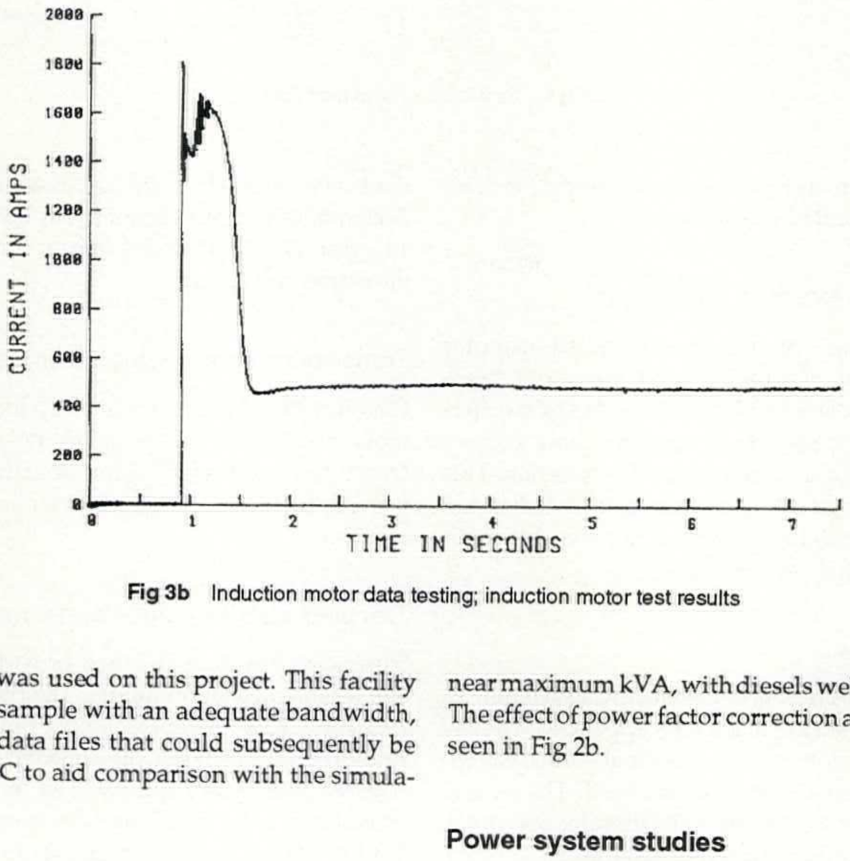

Fig 3b Induction motor data testing; induction motor test results

data logging system was used on this project. This facility had the capability to sample with an adequate bandwidth, and also to generate data files that could subsequently be manipulated on the PC to aid comparison with the simulation results.

STUDIES

Steady state analysis

An example of steady state analysis is given in Fig 2. This shows the variation of system power factor with ship's speed. The operational requirement of the vessel included significant periods to be spent at mid-range speeds. The poor power factor in this range results in generators operating at near maximum kVA, with diesels well below maximum kW. The effect of power factor correction at constant kVAR can be seen in Fig 2b.

Power system studies

A wide range of studies was conducted, with the aim of not just measuring the performance of the system with typical data values, but of optimising the system performance by modifying machine specification. Examples of studies conducted are given below.

Model building

Electrical machine and equipment models are presented in a menu format. Model building consists of drawing the

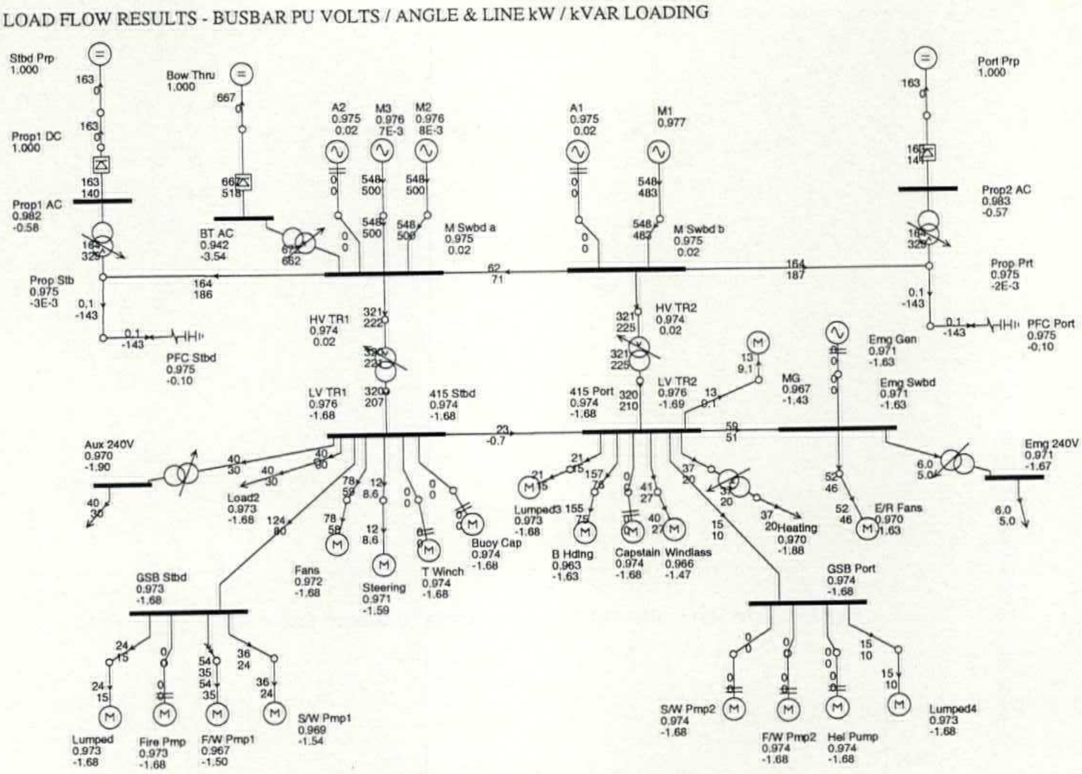

Fig 4 Simulated system load flow

configuration on screen and loading data – using Per Unit (PU) notation on a specified system base.

Transient response – induction motor start

Figure 3a shows the model prediction of an induction motor current during starting. Figure 3b shows the actual measured machine starting current. Whilst there is a slight difference in shape, the key characteristics of peak value, current decay profile and run-up time show good correlation. This example illustrates the point made earlier: the need to test individual equipment models in order to raise confidence in the overall system model performance.

Steady state load flow

Figure 4 shows the IPSA model of the electrical system with volts, load angle, and load kW and kVAR appended. The kW load of each induction motor represents the absorbed electrical power derived from the mechanical load. The overall accuracy of this type of load analysis is, therefore, as much dependent upon good mechanical load data, as it is dependent upon machine electrical data.

Short circuit analysis

The model provides short circuit data in two forms. It provides line current for each phase, demonstrating maximum prospective asymmetry (Fig 5a) and provides a kA or kVA value (making or breaking) at any point in the system at a specified time after application of the fault (Fig 5b). This flexibility is important, enabling accurate modelling of different devices interrupting the fault at different speeds. Fault level results from the electrical simulation, using initial design data and, subsequently, as-built data, demonstrated an error of less than 5% when compared to practically measured test results.

Transient response – generator step load change

Classical diesel generator set step load application and removal trials were conducted on the model, during factory trials and onboard. The results, shown in Fig 6, provide further good correlations between model and test results.

Transient stability – transformer magnetisation

Significant research did not provide an adequate transformer magnetisation model. The phase shift transformers rated at 1350 kVA represented a potential problem if, as a result of a failure at sea, they needed to be magnetised from reduced generator capacity. The worst case scenario was considered to be magnetisation from one 750 kW and one 364 kW generators running in parallel.

The transformer was modelled by a variable impedance giving an initial peak magnetisation current of 20 x Full Load Current (FLC) on infinite bars and decaying to steady state over a period of 250 cycles (5s). This represented the worst case available from empirical data.

Harmonic control and analysis

There are a number of elements to be considered when looking at the overall system harmonic performance, namely:

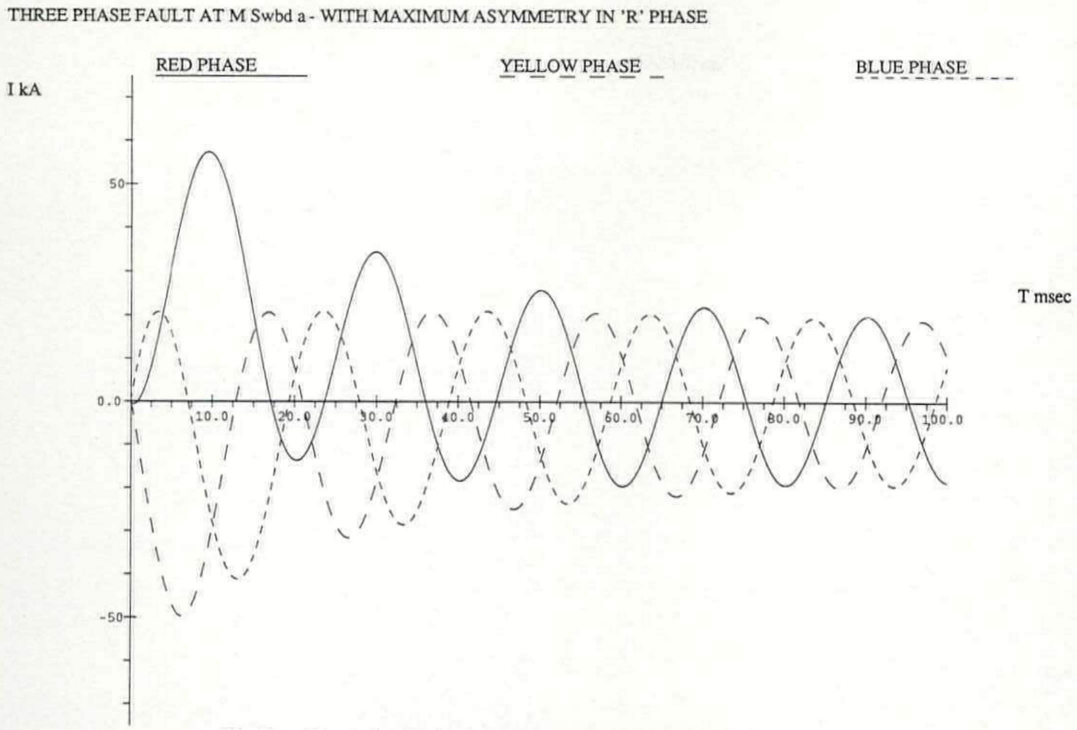

Fig 5a Short circuit simulation; simulated short circuit current waveform

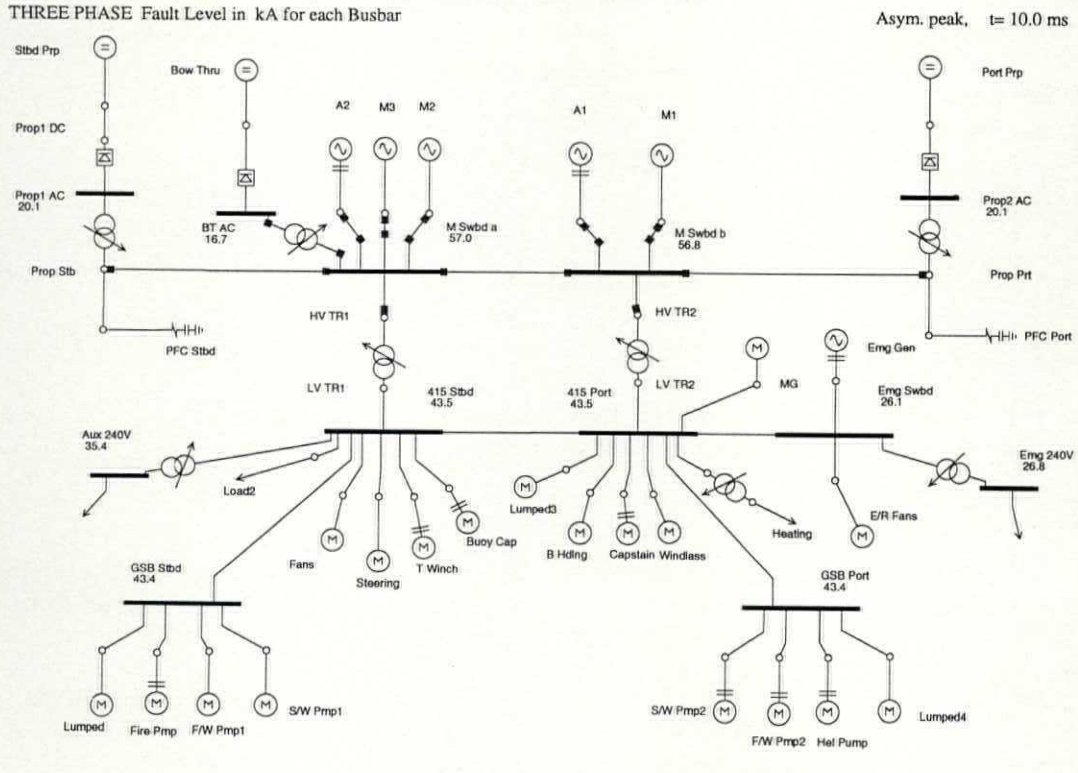

Fig 5b Short circuit simulation; simulated circuit breaker making ratings

1. Harmonic currents generated by non-linear loads (in this case the thyristor converters).
2. The effect of alternator characteristics on system harmonics.
3. The effect of the power factor correction units on harmonics.
4. The effect of harmonics on significant reactances and capacitances within the system.
5. The quality of power supplies at consumer terminals.

The full network model shows the Total Harmonic Distortion (THD) at different points in the system, without (Fig 7a) and with (Fig 7b) the power factor correction units in circuit.

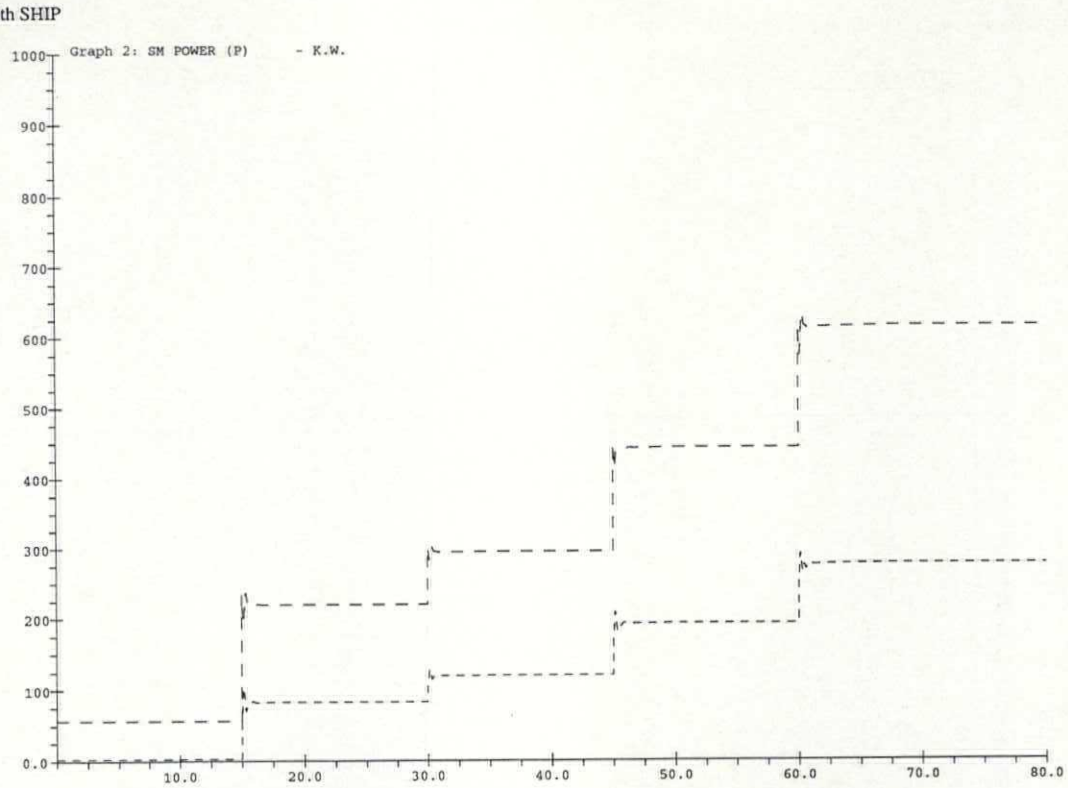

Fig 6a Step load response; simulated kW response

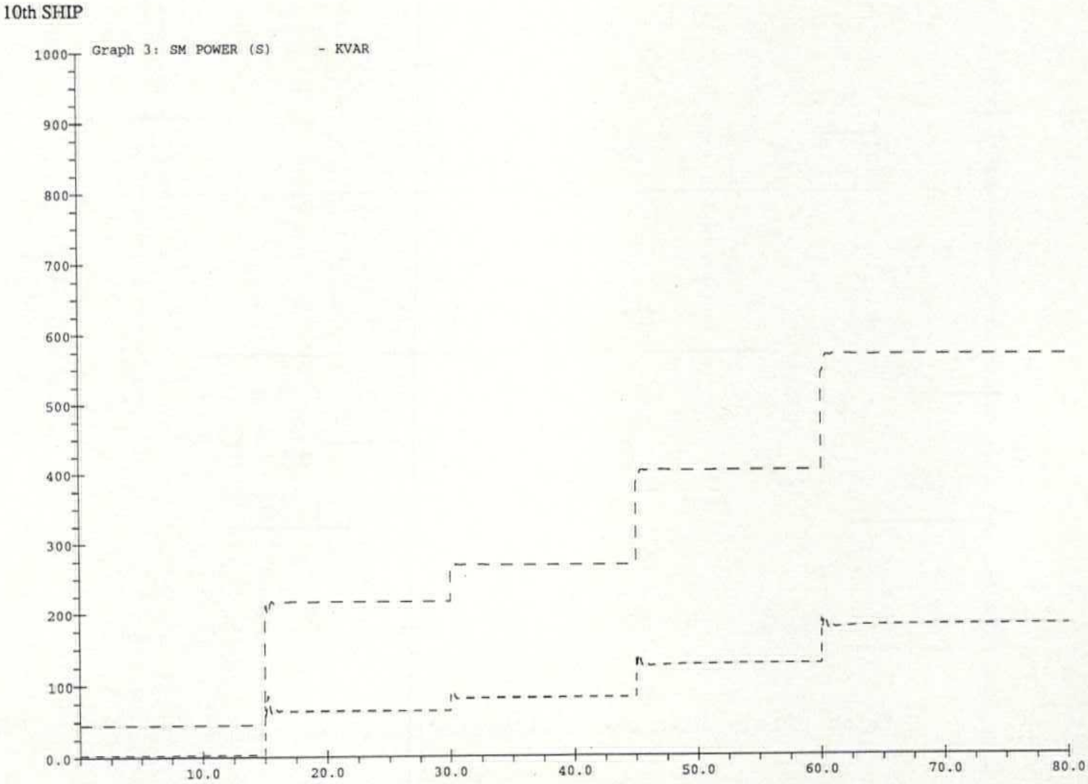

Fig 6b Step load response; simulated kVAR response

The harmonic current spectrum generated by 12-pulse converters can be, in practice, significantly different to the theory. Table I illustrates this point. (THDi is the total harmonic distortion of the current waveform.)

These practical variations are caused by phase shift transformer characteristics and firing circuit design. System voltage distortion becomes a product of both harmonic currents and the power generation and distribution system design.

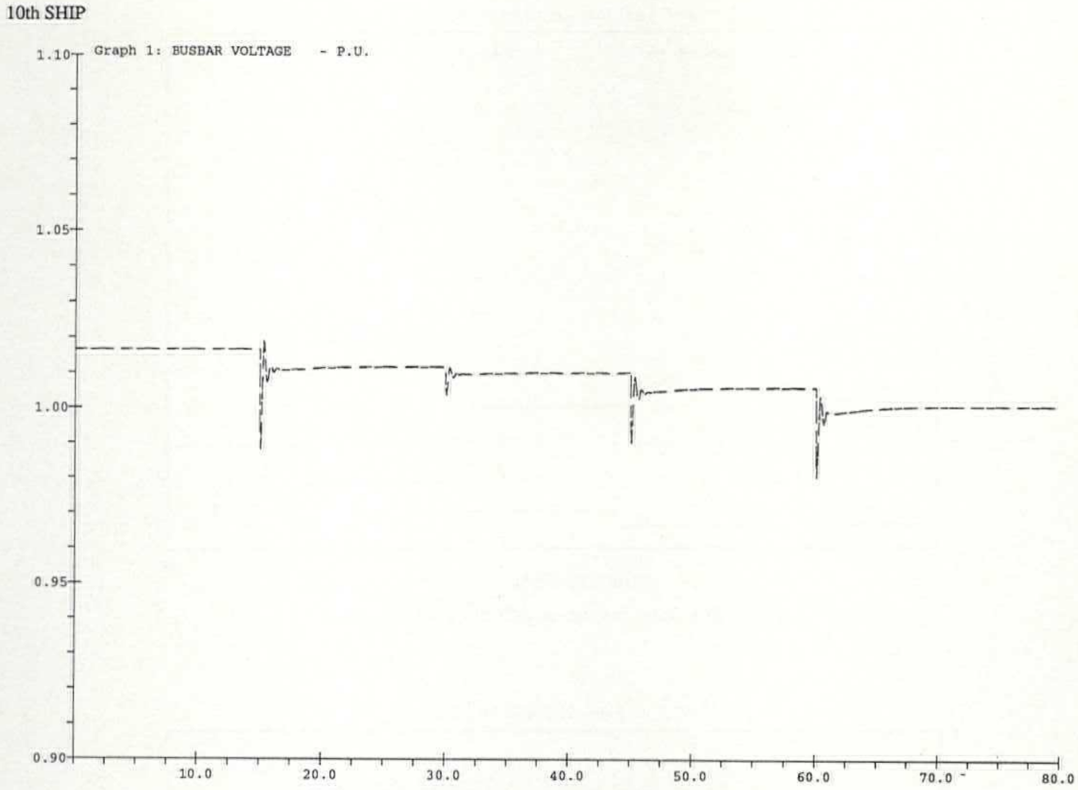

Fig 6c Step load response; simulated voltage response

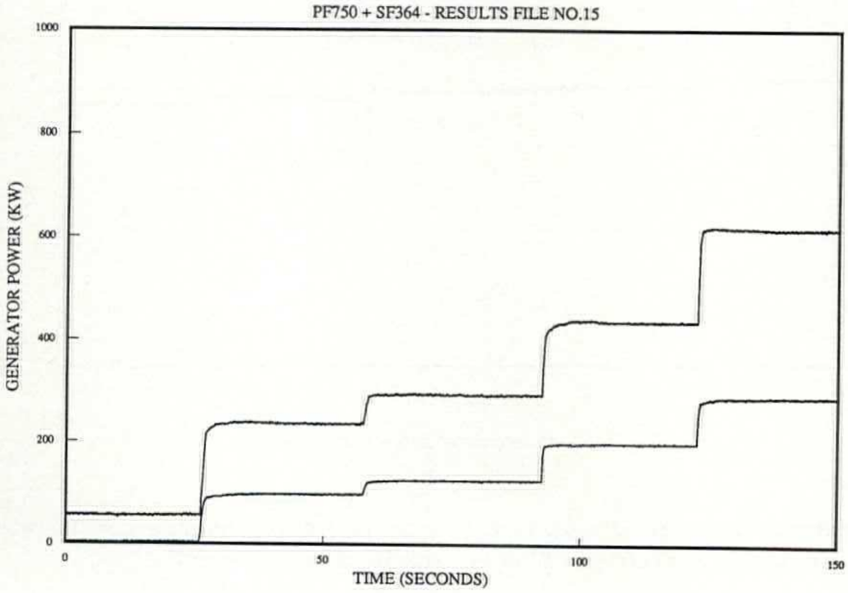

Fig 6d Step load response; actual kW response

Harmonic control is required in order to achieve an acceptable level of voltage distortion at consumer terminals, to avoid resonances, to minimise losses and to remove the need for de-rating equipment.

Alternator stiffness, in the form of sub-transient reactance (Xd"), has the major effect on the voltage distortion caused by harmonic current. The stiffer the supply (lower Xd") the lower the THD, but the higher the short circuit fault level.

The model used enables a trade-off study to be conducted. The results shown in Fig 7 are based on an Xd" of 10%. This produces fault levels within the capacity of the preferred range of circuit breakers and substantially reduces THD, as illustrated in Table II.

The figures in this table are illustrative only and based on simple converter/alternator circuits, without the effects of a full distribution network, parallel machines and transformers.

Power factor correction units

The justification for power factor correction (PFC) lies in improving fuel economy. The design of these units must

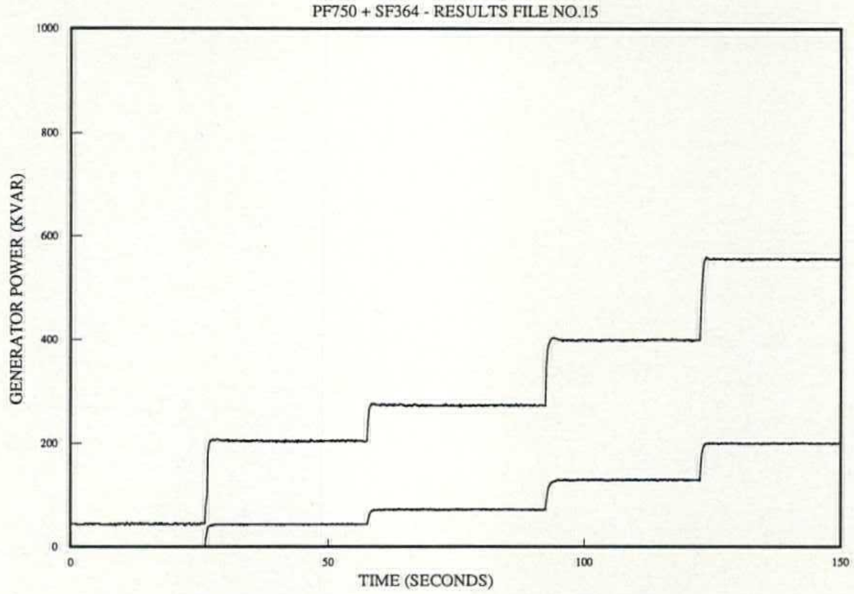

Fig 6e Step load response; actual kVAR response

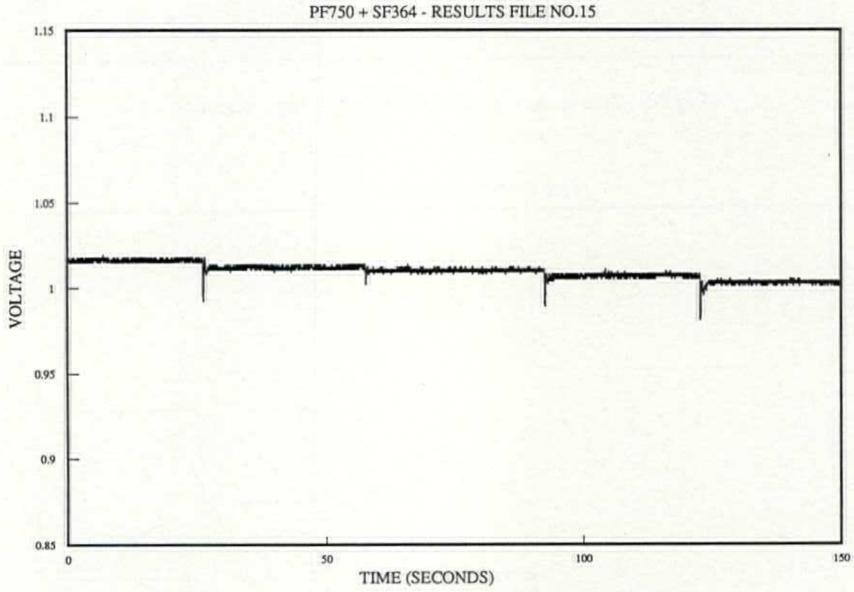

Fig 6f Step load response; actual voltage response

recognise the presence of harmonics to avoid resonances, and by careful design the units can act as a harmonic filter as a bonus.

The design target was 10% THD without filters. Since theoretical harmonic currents from thyristor converters are normally greater than the practical values, the model prediction of 8% THD worst case was expected, and proved to be pessimistic. Worst case onboard measurements without PFCs connected are <6%, and with PFC are <4% THD.

The harmonic penetration analysis provided by the model recognises both discrete components within the filter design and other reactive and capacitive components in the supply network. Resonances will therefore be identified at a component level by the model.

Figure 7 illustrates the attenuation of harmonics down to individual consumer terminals. These results, combined with transient stability studies and load flow studies, provide the full results necessary to predict the worst case quality of power supplies.

Protection co-ordination

Resulting from the chosen system fault level, the protection co-ordination (discrimination) through the distribution network can be designed and tested.

Once specified in the electrical simulation model, protection device tripping characteristics are operational in all transient stability studies, providing easy identification of any inadvertent or unwanted tripping operations.

Overall propulsion system simulation

The overall propulsion system simulation was implemented

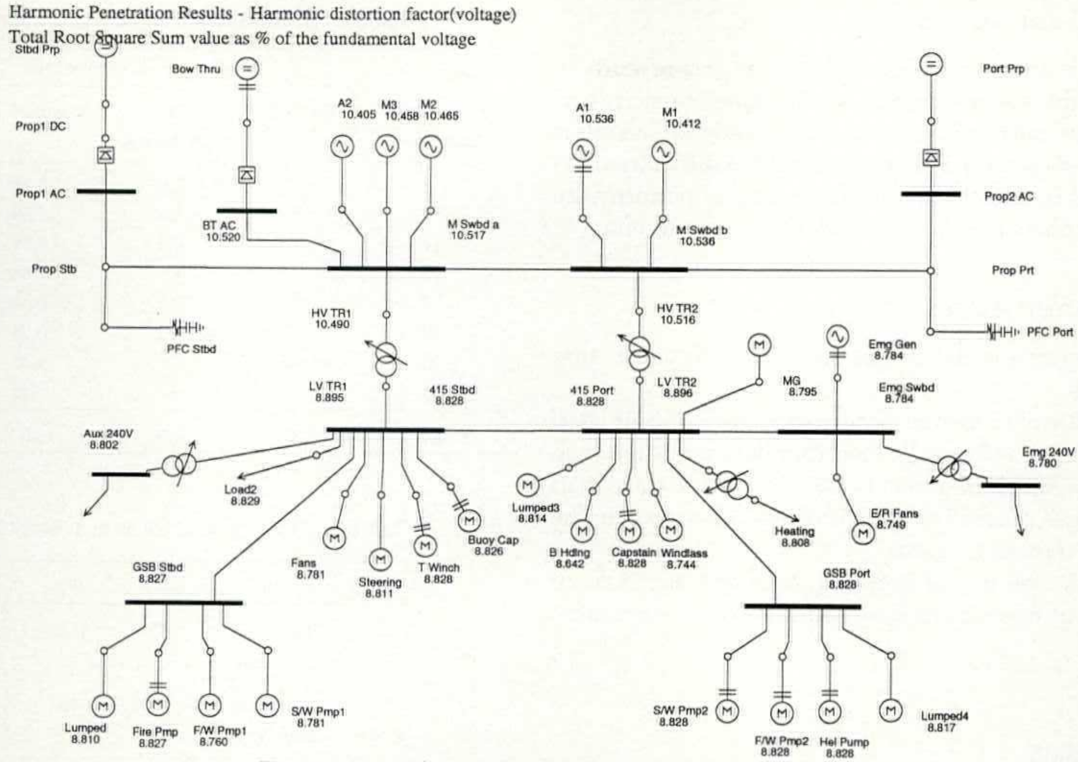

Fig 7a Harmonic analysis; harmonic levels without filters

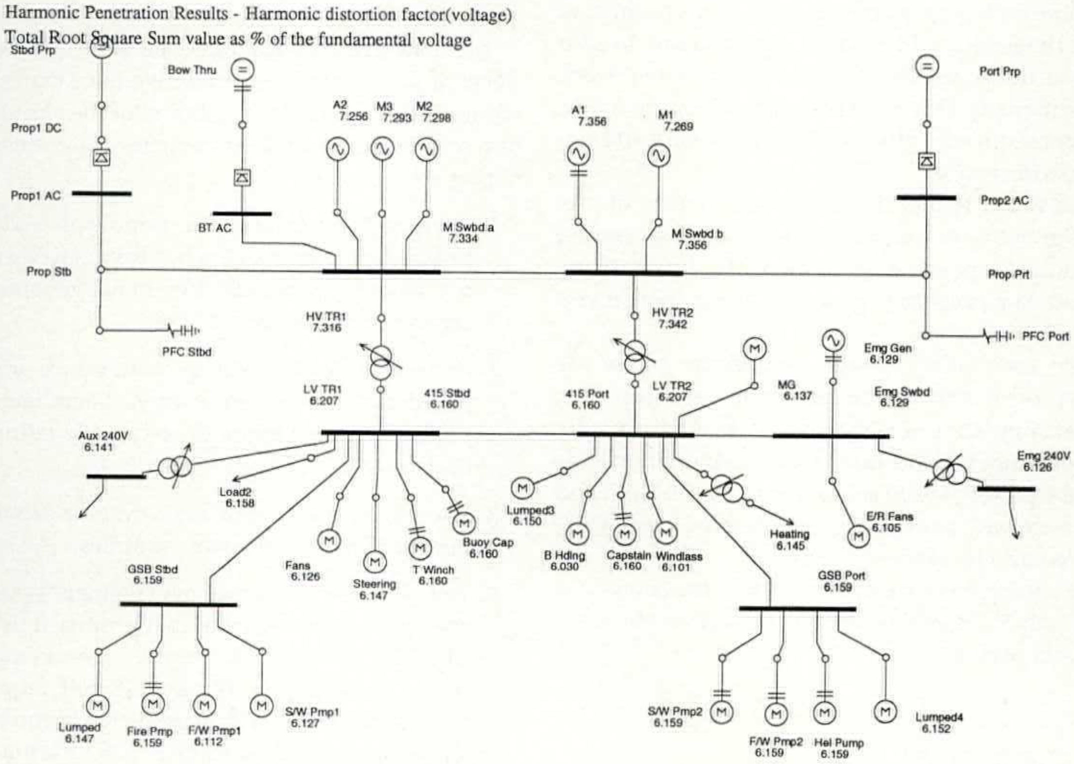

Fig 7b Harmonic analysis; harmonic levels with filters

on MATLAB-SIMULINK, which allows a structured and layered approach to model building. Figure 8 provides an illustration of different layers of the model, as they appear on the screen. These are supported by data tables at the lowest level in which equations, coefficients and constants are defined.

Fig 8a effectively defines the scope of the model. The propulsion control system is contained within block 1, and the power generation and power management systems in block 2.

Manoeuvre simulation

In order to compare trials results with simulation results, the original model has been programmed to reproduce lever movement sequences recorded during trials.

Slow speed manoeuvres

Slow speed manoeuvring was a particular area of study in order to ensure that maximum use of installed capacity was made. The overall fit between simulation and trials results is very good – especially bearing in mind the difficulty often encountered in modelling transient propeller performance and hull/propeller interaction under these conditions.

Crash stop manoeuvres

Figure 9 shows simulated (9a) and trials (9b) crash stop manoeuvres.

At t=2970 in Fig 9b, a significant perturbation in both shaft speed and motor volts can be seen. (Similar small effects can be seen at t=2920–2950 and at t=3080–3100.) These are shaft speed changes caused by hull/propeller interaction in the slow speed transient regions.

The crash stop overall stopping time and ahead reach measured during sea trials were within 5% of the simulation predictions.

PROGRAMME

The programme for this project is significant for a number of reasons. The timescale of 18 months from contract to ship acceptance was not generous, given the development work planned. Additionally, this was a commercial contract, with commercial consequences attached to late delivery and unsatisfactory performance.

In addition to the 18 month period, two months of preliminary design work in support of the tender was carried out. This included a power system model first-pass, using estimated load data to confirm generator sizing, fault levels and harmonic penetration.

During the preliminary design and tender phase the decision was taken that the overall timescale was acceptable, provided that simulation was extensively used during design. Past experience had indicated that the simulation tools available to the project would enable rapid model build and provide the necessary confidence level needed for key design decisions early in the design process.

The short setting-to-work and sea trials programme is attributed largely to the extensive use of simulation throughout the contract period.

SERVICE EXPERIENCE

In the 18 month period since vessel hand-over, a practical involvement has been maintained with the Northern Lighthouse Board (NLB) and MV *Pharos*, both in respect of fulfilling hardware guarantee obligations and, subsequently, with assisting NLB in satisfying classification society periodic survey requirements. Throughout this period it has proved possible to validate simulation predictions over an extended timescale and, indeed, to apply simulation to assessing and implementing an owner's request for enhanced vessel performance.

Table I 12-pulse converter harmonic currents

Harmonic number	*Theoretical*	*IEEE (Refs 3 and 4)*	*Manufacturers*	*Measured*
	% of fundamental			
5	0	2.6	3.36	1.2
7	0	1.6	1.68	0.7
11	9.1	4.5	9.08	4.4
13	7.7	2.9	7.68	3.4
17	0	0.2	0.84	0.4
19	0	0.1	0.55	0
23	4.3	0.9	4.33	0.6
25	4.0	0.8	3.98	0.4
THDi	13.3	6.3	13.8	5.8

Table II THD and fault levels at different Xd"

Xd"	*15%*	*10%*
THD (12-pulse)	15%	11%
Fault level (Making kA)	50	66

In broad terms, no fundamental defects with the vessel's electrical and control system design have materialised, providing further practical validation of the simulation activities undertaken and their benefits. Key elements worth noting are:

1. Energisation of the main propulsion and bow thrust phase-shift transformers has been successfully carried out from a single 750 kW main generator, with no tripping of protection devices.
2. Protective device settings remain, as originally proposed by the IPSA simulation. There has been no reported spurious tripping or cascade failure of protection devices.
3. There is no evidence of any harmonic problems or poor quality of electrical power supplies.
4. The NLB specific power management system is fundamentally unaltered from that proposed by the original MATLAB-SIMULINK propulsion simulation, and continues to satisfy NLB's operational requirements. A considerably higher than predicted harbour load necessitated adjustments to some PMS thresholds, to enable this load to be supported by a single 365 kW auxiliary generator, whilst maintaining adequate safety margins. Simulation was used to determine the revised thresholds and ensured a fast and trouble free implementation.

One particular request received from NLB, was to investigate the feasibility of enhancing the vessel's stopping performance above that originally accepted during trials. The MATLAB-SIMULINK propulsion model provided a validated platform for investigating this request and, in particular, for assessing the benefits or otherwise of changing

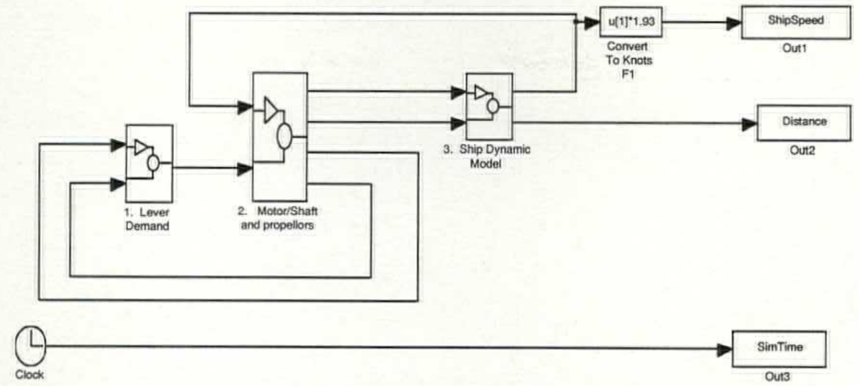

Fig 8a Propulsion system simulation; top level simulation

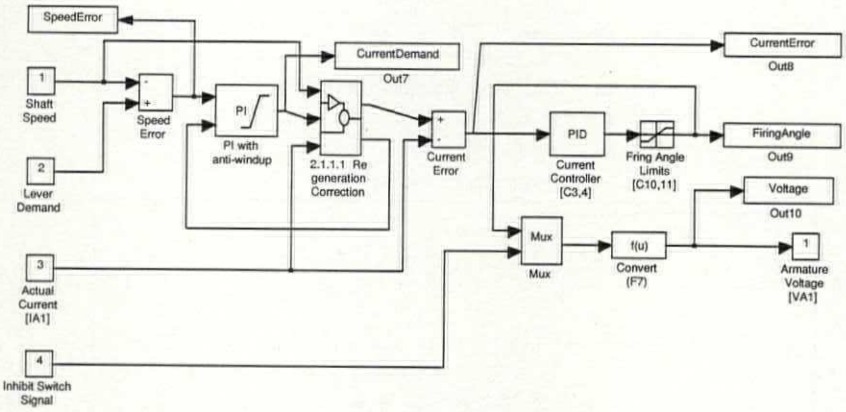

Fig 8b Propulsion system simulation; motor controller simulation

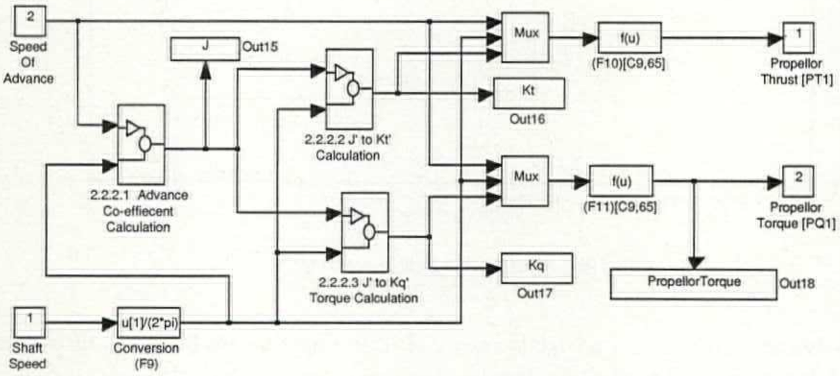

Fig 8c Propulsion system simulation; propeller thrust and torque simulation

propulsion motor regeneration limits and speed/current ramp rates. Figure 10a shows a simulation of the vessel's stopping performance as accepted during trials and Fig 10b a simulation of the enhanced performance which could be achieved.

Table III shows a comparison of vessel performance post-modification with that predicted, and that for pre-modification for a crash stop manoeuvre from maximum ahead speed.

The modification was implemented with minimal disruption to vessel operation and precisely in accordance with the parameters derived by simulation. Key elements of the modification were an increase in the propulsion motor regeneration level and a slowing down of the rate at which shaft reversal occurs, thus decreasing the amount of propeller cavitation and increasing 'bite'.

CONCLUSIONS

The Diesel Electric Propulsion System outlined benefited significantly from the use of modern simulation tools.

The level of innovation in terms of harmonic control, power factor correction and load control could not have safely been achieved within the timescale, without the use of these tools – and the engineering expertise to apply them.

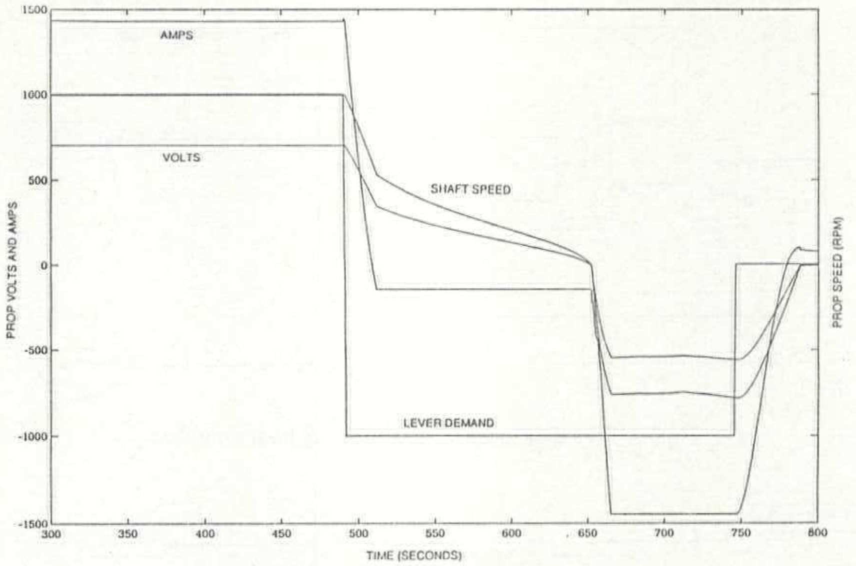

Fig 9a Crash stop; simulated crash stop

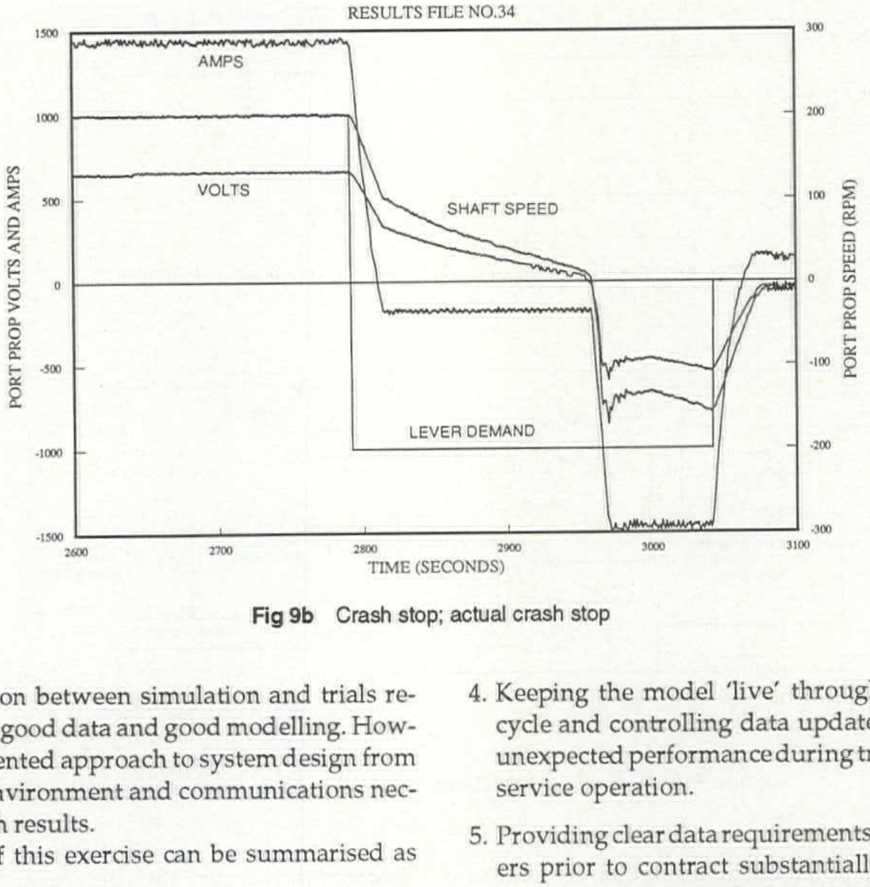

Fig 9b Crash stop; actual crash stop

The close correlation between simulation and trials results is attributable to good data and good modelling. However, a simulation oriented approach to system design from day one creates the environment and communications necessary to achieve such results.

The key aspects of this exercise can be summarised as follows:

1. The quick build of a preliminary model enables fundamental design decisions to be made early and also provides key specification data for long lead equipment.
2. An object oriented approach to model building, coupled with the design engineer hands-on facility offered by modern simulation tools, creates a greater system performance awareness in the design team.
3. Planning from the outset and proper trials recording in order both to validate models and improve the database are essential.
4. Keeping the model 'live' throughout the project lifecycle and controlling data updates reduces the risk of unexpected performance during trials or subsequent in-service operation.
5. Providing clear data requirements to equipment suppliers prior to contract substantially improves both the quality, timescale and cost control of the exercise.
6. Maintaining up-to-date validated simulation models throughout the operational life of a vessel provides the owner or operator with a service which permits simple and realistic assessment of any proposed enhancements or changes to vessel performance.

Regarding the use of simulation in the design of diesel electric propulsion systems, a number of observations can be made. There is substantial scope for further innovation and optimisation in these systems. Unlike mechanical systems, the majority of the parameters within electrical systems are

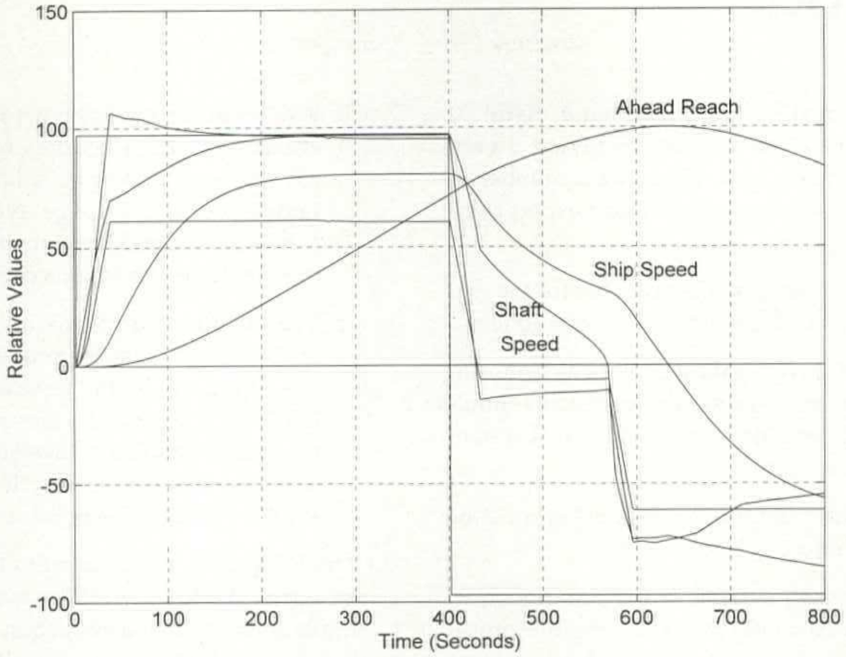

Fig 10a Northern Lights marine results; crash stop pre-modification

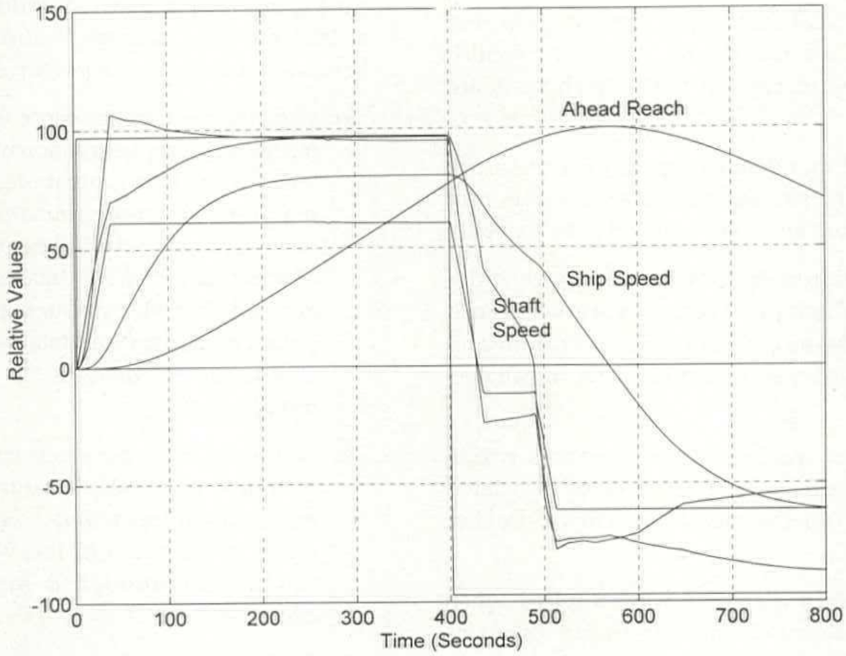

Fig 10b Northern Lights marine results; crash stop post-modification

Table III Enhanced vessel stopping performance

	Trials – pre-modification	*Simulation – predicted*	*Trials – post-modification*
Initial vessel speed (kn)	14.2	14.3	14.4
Shaft speed at start of regeneration (rev/min)	120	120	120
Time from lever movement to shaft reversal (s)	160	90	97
Time from lever movement to dead in water (s)	210	155	150

invisible, and only receive scrutiny if there is a problem. Simulation provides visibility. Visibility aids understanding and analysis, the essential ingredients for improvement.

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Discussion

Lt R D Hayhoe RN (Naval Support Command, Bath) I would like to congratulate the authors for giving a very interesting and informative paper. There are a number of issues on which I would welcome the authors' expert commentary.

1. Would the authors expand on the potential for the real time implementation of their simulation technique as:
    a. a design tool for investigating plant behaviour (incorporating power and propulsion systems simultaneously) and defining associated control system requirements;

    b. an aid to human factors studies and ergonomic design of machinery control rooms;

    c. a combination with suitable hardware models in order to build cost effective and versatile procedural trainers for the coaching of ships' marine engineering staff.

2. Do the authors perceive their style of plant modelling causing a philosophical shift in the marine engineering industry's attitude towards sea trials, and any significant changes in the manner in which such trials are conducted?

3. The authors stated that detailed operational performance data required for simulations were requested from manufacturers before any contracts had been placed.
    a. Since the selection of equipments was greatly influenced by simulated plant performance, how much reticence did the project team encounter from prospective machinery suppliers in disclosing all necessary data?

    b. Were simulated machinery performances within the overall system model fed back to the associated manufacturer (for the mutual benefit of supplier and customer)?

4. What quality assurance criteria were applied when requesting, and in scrutinising, the source data sets supplied for simulations?

5. How were the boundary conditions for discrete data sets initially defined, and subsequently refined, for overall propulsion system simulation?

P H Sallabank and A J Whitehead (Vosper Thornycroft Controls, Portsmouth)

1. Modern computer hardware enables real time, or faster, analysis of complex marine power and propulsion systems.
    a. The authors' company have successfully applied this technology to defining power and propulsion control system requirements, and to investigating/optimising the interaction between items of electrical, control and propulsion plant.

    b. Whilst simulation has not, to date, been applied to ergonomic design studies for machinery control rooms, the technology available allows display parameters and screen page layouts for VDU displays to be assessed and developed with confidence during the design phase of a project.

    c. The facility of undertaking real time simulation leads logically into the provision of training facilities supported by the same simulation. Whilst the MV *Pharos* simulation was not used for this purpose, the technology is available to achieve this and is indeed being applied by the authors' company in the field of ship position control systems.

2. A philosophical change in attitude towards sea trials is not currently foreseen. The availability of accurate simulations enables a reduction in sea trial duration through the ability to undertake a considerably greater degree of validation during the design phase of a project. Accurate simulation enables 'tuning' to be undertaken during design, not by what could historically be called a 'trial and error' approach during sea trials; this has been validated by our experiences on MV *Pharos*.

    3a. Surprisingly little reticence was encountered from machinery suppliers concerning provision of simulation data. This is attributed to the fact that data requirements were nominated to suppliers prior to hardware contract placement and did not form part of separate contracts; data was generally supplied at no additional cost. Our experience indicates that obtaining simulation data as a discrete item, even post-hardware delivery, is normally achievable, but at a cost.

    3b. Simulated machinery performances, both from the overall system model and from individual equipment validation models, were fed back to the associated manufacturers; this was an integral part of model validation and system development/optimisation.

4. Quality assurance for simulation data, in our experience, relates to the accuracy of the data supplied by equipment manufacturers. Our normal practice is to apply tolerances contained in British, European or International Standards, as relevant to individual items of equipment. The accuracy of simulation output is more heavily dependent on certain key parameters than others; we have undertaken an extensive amount of sensitivity analysis on simulation data and, based on this, in some circumstances we will specify considerably tighter, but realistic and practically achievable, tolerances.

5. At all stages of the simulation, from proposal to vessel handover, the most realistic data available was obtained from manufacturers. For some manufacturers, achieving equipment performance in accordance with simulation data was a contractual requirement. At all stages of

the project, equipment performance was checked against overall propulsion simulation predictions, thus maintaining the simulation as a 'desk top prototype' throughout the project life cycle.

Dr G Armstrong (Three Quays Marine Services Ltd) May I, firstly, thank the authors for their paper and the presentation which, for me, is very much preaching to the converted: I am strongly in favour of propulsion simulations being done at the design stage. Sea trials can be busy enough and anything which can be done to reduce the uncertainty is, of course, extremely helpful. Time spent on sea trials is an expensive way of fine tuning the control system.

Could the authors give more detail on the simulation timescale in relation to the design period? Was ship data and the model available in time to influence the design, and if it was possible to improve the performance of the ship after delivery, could this not have been done at the design stage?

Secondly, Fig 7 of the paper is based on a value for Xd" of 10%, which, I believe, is a conservative value for subtransient reactance. Was this value specified as a result of the simulation?

P H Sallabank and A J Whitehead (Vosper Thornycroft Controls, Portsmouth)

1. Simulation formed an integral part of the MV *Pharos* project from the proposal stage, through detailed design, factory acceptance, basin trials, sea trials and in-service operation. Data was available from manufacturers in time to influence design. In some circumstances, early simulation enabled us to specify equipment parameters to manufacturers as part of performance criteria.

2. The ship performance improvement undertaken after delivery relates to vessel stopping performance. MV *Pharos* utilises a regenerative braking system during stopping, exporting power from the fp propellers into the electrical power system. As-delivered, the vessel satisfied the owner's performance requirements, whilst maintaining a conservative approach to regeneration and stressing of equipment. With the benefit of the experience of a number of months of in-service operation, an improvement in stopping performance was considered feasible without infringing safety margins. This was possible due to a higher than expected hotel load on the vessel and greater experience of the propeller's four quadrant transient performance characteristics.
   Hull/propeller interaction in the transient operating regime is notoriously difficult and unreliable in terms of model performance. A conservative approach is therefore necessary for ship and machinery safety reasons. The result is often a larger than necessary safety margin measured at sea, with the scope to improve manoeuvrability without infringing prudent safety margins.

3. Alternator sub-transient reactance values were specified to the alternator manufacturer as a direct result of simulation. Sub-transient reactance values directly affect electrical system fault levels and harmonic levels; a 'trade-off' study involving technical performance and equipment costs was undertaken, leading to choice of optimised sub-transient reactance values.

J Walker (BMT Defence Services Ltd) I noted that the accuracy of modelling of electrical machines has achieved high standards and, indeed, the presentation showed a difference of approximately 1% in one case between modelled (from design data) and actual (from trials results) response. I also noted Mr Sallabank's comments with respect to propeller transient characteristics where the lack of information at the design stage had been overcome by experienced judgements, but that these problems were not as critical as propeller diameter. With these comments in mind, I would wish to determine which aspects of modelling are most critical in a simulation exercise and which aspects are still considered to be the greatest unknowns or risks at this time.

P H Sallabank and A J Whitehead (Vosper Thornycroft Controls, Portsmouth) Modelling of the electrical generation and propulsion system contains little risk and few, if any, unknowns. Equipment and control system models are well established and validated, the principal risks relating to data quality and experience of the simulation operator. One area which does contain risk is the modelling of magnetising inrush currents into a transformer – significant research on our part has not uncovered a suitable model.

For the overall propulsion and vessel performance simulation, the areas of greatest unknown are transient four quadrant propeller modelling, cavitation and complex water flows around the stern of the vessel.

G T Gerrard (Laing Oil & Gas) Thank you for a very absorbing and useful paper.

My questions are as follows:

1. It would be interesting to know the reasons for selection of dc propulsion motors rather than ac motors with variable frequency drives.

2. Your comments on transformer magnetisation with reduced generation capacity, particularly the long decay period, were surprising. I would appreciate knowing over how much of this period the effect produced a current significantly over full load.

P H Sallabank and A J Whitehead (Vosper Thornycroft Controls)

1. The use of dc rather than ac propulsion motors was specified by the owner and their consultants. MV *Pharos* utilises two 1 MW propulsion motors and, at the time of the initial design, dc motors and controllers offered considerable cost savings over equivalent ac technology. Issues of motor size and weight were not crucial to the design of *Pharos*, nor is motor maintenance, in particular brush wear, given the vessel's operating profile.

2. Transformer magnetisation produced a primary current significantly in excess of full load current for a period of approx 0.5s with abnormal reduced generation capacity.