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Integrated Electrical and Mechanical Modelling of Integrated-Full-Electric-Propulsion Systems

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Abstract

Integrated Full Electric Propulsion (IFEP) systems are the subject of much interest at present. Current research is focused on analysing and improving aspects of subsystem and system performance. However, there is a great need to look more widely at the 'multi-physics' problem of characterising the dynamic interactions between the electrical and mechanical systems. This paper will discuss the changing nature of modelling and simulation to aid research into IFEP systems, outlining the alternative angle taken by the Advanced Marine Electrical Propulsion Systems (AMEPS) project to characterise and investigate electrical-mechanical system interactions. The paper will describe this approach and highlight the unique challenges associated with the problem, discussing the suitable methods that will be adopted to address these challenges. Finally, an overview of the present and future research opportunities facilitated via the AMEPS project will be presented.

1 Introduction

Recent years have seen an increasing trend towards more-electric power distribution within the marine sector, which aims to replace mechanical and hydraulic power systems with electrical equivalents [1-2]. Integrated Full Electric Propulsion (IFEP) embraces this concept by seeking to replace the traditional combination of a mechanical power distribution system to drive the ship's propulsion, and an electrical power distribution system to supply ship's services, with a common electrical power system to supply both. It is anticipated that such a move will bring benefits of increased design flexibility, optimised power management, reduced fuel consumption, reduced maintenance and increased operational flexibility [2].

The IFEP concept is witnessing significant research into many aspects of the system level, subsystem level and component level electrical technologies. However, the interactions between the dominant mechanical systems (turbines, reciprocating engines and propulsors) and the electrical systems are not fully understood. In the analysis of such a physically compact, limited inertia system, the validity of considering these systems in isolation, or representing their interactions in a simplistic form is open to question.

As a result, the Advanced Marine Electrical Propulsion Systems (AMEPS) project has been initiated to develop fully integrated models of IFEP systems, from the prime movers through to the propulsion systems, in order to investigate the interactions between these systems and the electrical network. The project involves pooling the expertise of Cranfield University, the University of Strathclyde and the University of Manchester to develop and integrate dynamic models of prime movers, electrical distribution systems and propulsor systems (including power electronic drives) respectively, to provide a flexible electrical-mechanical modelling and simulation capability. Figure 1 illustrates the AMEPS concept.

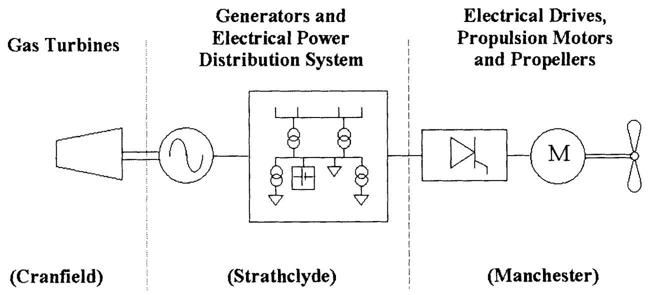


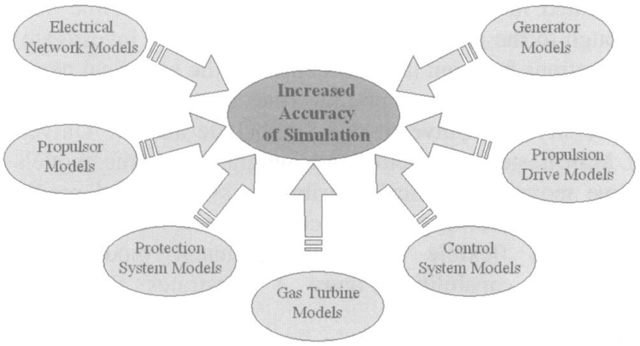
Figure 1: AMEPS system schematic

2 Research Approach

Existing IFEP related research projects cover a wide range of technological fields. There has been a recent rise in the number of projects investigating the dynamic and transient performance of the electrical power distribution system through modelling and simulation [3-6]. As the mechanical systems discussed earlier are frequently the cause of such transients, these systems are being modelled at a higher degree of fidelity in order to obtain increased levels of accuracy from the simulation. However, in most cases, it is necessary to simplify the impact of the mechanical systems on other systems to reduce the computational burden of the simulation. Indeed, the high levels of complexity associated with system level simulations of IFEP systems often make it necessary that simulations be configured specifically to investigate the desired phenomena at the level of detail necessary.

The AMEPS project aims to take an alternative and more comprehensive approach to system-level modelling and simulation than many previous efforts. Rather than strive for increased accuracy of network simulation and incorporating certain aspects of system interaction almost as a secondary consideration, this project is focused on investigating the interactions that take place at the boundaries between the electrical and mechanical systems during dynamic and transient events. The modelling and simulation is configured to develop as much interaction between system models as possible at multiple levels of detail. Figure 2 illustrates the AMEPS research approach.

Overview of Existing IFEP Research Projects



AMEPS Research Approach

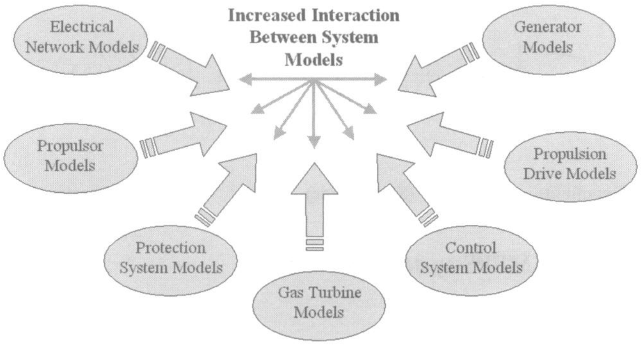


Figure 2: Illustration of IFEP research approaches

3 Challenges and Solutions

The development of a flexible and integrated model presents some significant challenges. The first of these is the design and development of appropriate interfaces between subsystem models to allow the electro-mechanical interactions to take place. One of the key aspects to this is developing the interfaces to allow bidirectional data flow at a suitable degree of accuracy and time resolution. The nature of the system-level interactions is such that conventional models with predefined inputs and outputs are no longer sufficient in characterising and facilitating investigation of behaviour under all necessary scenarios. Input quantities for a particular model during one simulation may be output quantities in another, or even in the same simulation, but at a later instant. Hence these varying demands on the interfaces can require that several interface structures be developed. The development of a library of integrated models requires that each proposed interface structure be assessed in detail to ascertain its operating limits and shortfalls. For example, it can readily be anticipated that the naturally occurring algebraic loops at the system interfaces will reduce the stability of the overall model. This may produce invalid results following some state changes in the model operating conditions or increase computation times.

The second main challenge is addressing the issues of the markedly different time constants associated with the mechanical and electrical systems. Representing the operation of power electronic converters within a model containing much slower mechanical systems such as gas turbines and propellers requires an adaptive approach to minimise model complexity (hence improving simulation speed) whilst not sacrificing relevant accuracy. This requires that the subsystem models be developed in suitable formats to allow different levels of detail to be studied. This again will require that a library of models for each subsystem be produced in order to facilitate this.

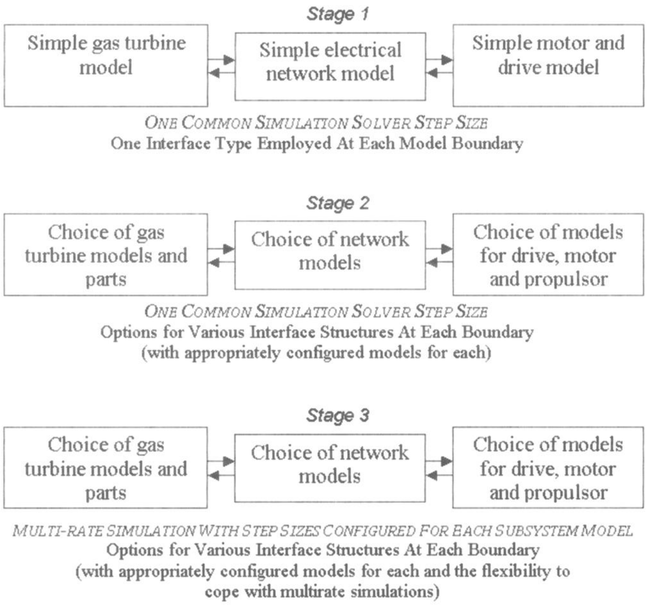


Figure 3: AMEPS model development Strategy

Figure 3 illustrates the proposed development plan for the AMEPS integrated modelling environment. It incorporates all of the aspects discussed above and its evolutionary form will allow the format and structure of the models and interfaces to be assessed early in the development process without utilising unnecessary levels of detail. When progress in this area of investigation is complete, development of a wide range of models configured to suit the interfaces can begin. At this point, investigations will be conducted to consider methods for multi-rate simulations of the integrated model. All of these factors should allow meaningful and efficient research into the interactions between the dominant mechanical and electrical systems within IFEP networks.

4 Research Opportunities

The alternative research angle taken by the AMEPS project provides the opportunities for unique research and investigation into IFEP systems.

4.1 Opportunities in Prime Mover Design

The integrated model will provide an interactive simulation platform to allow the evaluation of steady-state and transient performance of simple and advanced cycle gas turbines and their components when utilised for IFEP systems. Because of their higher efficiencies than the simple cycle gas turbine, cycles that take advantage of the heat-exchange phenomenon such as the Intercooled-Recuperative (or regenerative) Cycle (IRC) and Air-Bottoming Cycle (ABC) are of particular interest. Investigating the two-way interactions that occur between the gas turbine and generator within an IFEP environment is extremely also useful for aiding the understanding of the effects of these heat ex-changers (intercooler, recuperator or regenerator) in the transient performance of the prime mover. In addition to this, by simulating the gas turbine operation during extreme conditions, faults and reconfiguration events that may be experienced in IFEP systems, the boundary operating limits can be established in order to design suitable protection control systems.

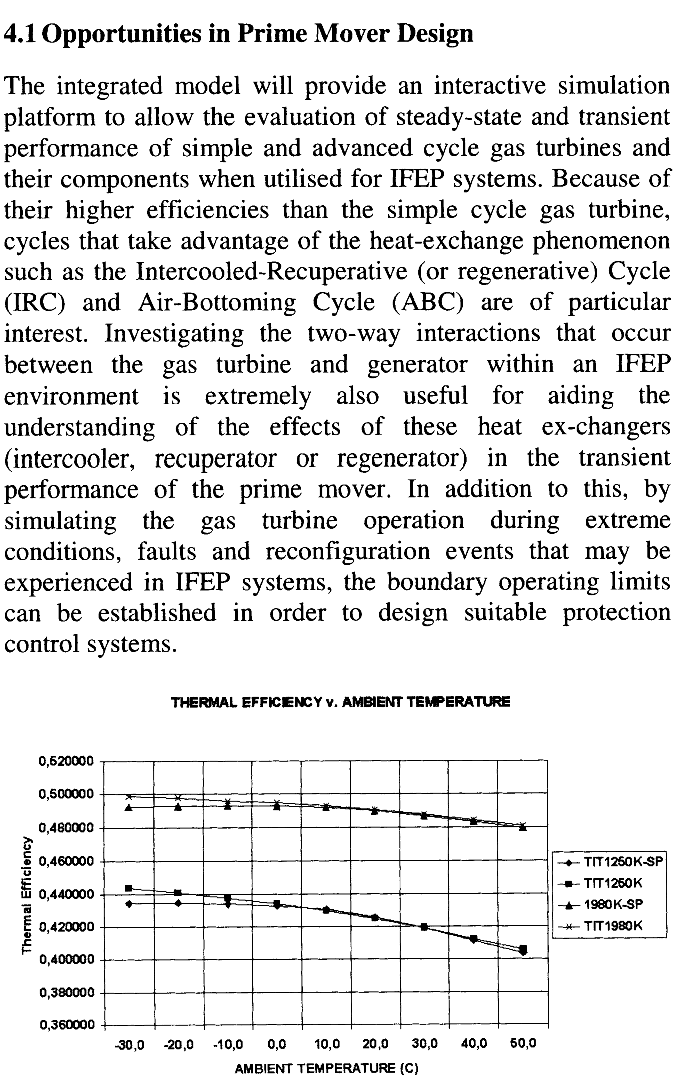


Figure 4: Low and High TIT Comparison Between Single Spool and Two Spool (Power Turbine) Recuperative Gas Turbines

The simulation of the interactions between the prime mover and generator will also enable the comparison of different thermodynamic cycles and spool arrangements under various operational conditions and scenarios. The number of spools utilised is of particular interest, as this does not significantly change the steady state performance of the prime mover but is a key factor in the transient performance. Figure 4 demonstrates the steady state similarities by showing the efficiencies for a single spool machine and two-spool machine (with free power turbine) for different turbine inlet temperatures (TIT). However, under transient conditions, such as those imposed by the electrical system and generator, the single spool machine has a faster response and has a superior capability to cope with a sudden loss of power with less speed overshoot (as a result of its higher inertia) [7].

4.2 Opportunities in Propulsion Motor Drive Design

There is no single preferred solution for the propulsion drive system. Cycloconverters are proven technology in cruise ships and other applications, but produce high levels of supply and motor harmonics, audible noise and vibration [8]. IGBT inverters are favoured for their waveform quality, but do not have the voltage withstand capability for the higher power motors, hence there is an interest in multi-level inverters [8]. Many questions still exist about the interface between the power system and the propulsion drive. The diode bridge rectifier introduces high levels of harmonic currents into the power network and is not capable of bidirectional power flow. Possible solutions include a separately-generated clean bus for sensitive loads, passive or active filters to clean up the network, or use of a 12 or 18 pulse rectifier and phase shifting transformers or a fully-controlled bridge, to reduce the amount of harmonics produced. Each option has space, cost and reliability implications [8]-[9].

There is a clear move towards the use of podded external drive units, where the motor is directly coupled the propeller and both are contained in a streamlined pod which is mounted beneath the hull [10]. The pod can be rotated for positioning control as well as forward thrust. This arrangement gives improved hydrodynamic performance which more that offsets the losses introduced by the power conversion stages. Hence the key motor design parameter is high power density at high torques and low speeds. Traditionally synchronous motors have been used. Other candidates include the multiphase induction machine (in use now [11]) and permanent magnet and high temperature superconducting synchronous motors [12]-[13].

A key issue is how the propeller interacts with the rest of the system. Extreme conditions include a 'crash stop' (when the ship is brought to a halt in the minimum time, returning power which must either be absorbed by the power system or dissipated in a resistive load) and partial lifting of the propeller in high seas (giving a repetitive fluctuating load as the ship crosses wave fronts) [14]. Because propulsion forms the dominant part of the ship's electrical load these extreme conditions have the potential to cause power fluctuations in the power network

Hence there is a need to be able to compare propulsion drive systems, including the effects of load and supply disturbances, and in terms of harmonics and fault tolerance.

The propulsion drive cannot be looked at in isolation, because faults on the power network will affect the drive, and shock loads or faults within the motor will affect the power network. Similarly, the impact of harmonics depends on the generators and other driven loads in the network.

Propulsion drive system models will be validated on the test rig at the University of Manchester laboratories, shown in Figure 5. The test rig comprises a 3 phase rectifier, a purpose-built 12 phase inverter and a multiphase induction motor with a dynamometer load. The motor and inverter can be configured for 3, 4, 6 or 12 phase operation, with gating signals sourced from either an gate array (open-loop) or a dSpace microprocessor development system (closed loop). Validation studies will look at supply failures, load fluctuations and motor/inverter faults.

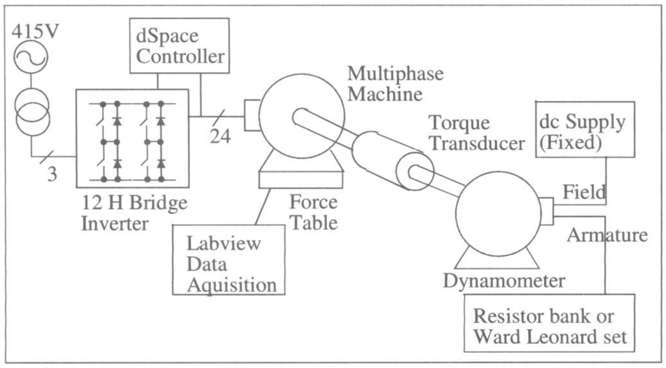


Figure 5: Propulsion drive validation rig

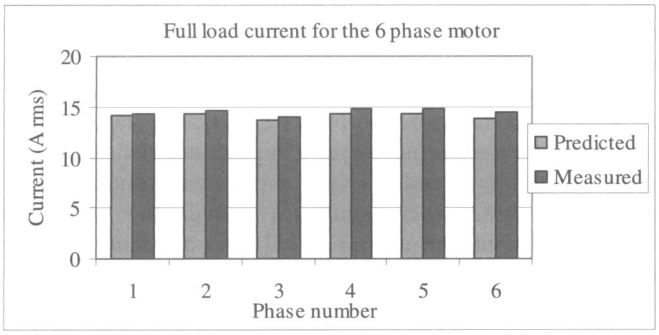


Figure 6: Comparison of measured and predicted motor phase currents for a 6 phase motor at full load.

Figure 6 compares measured and predicted motor currents for a six phase motor, using a steady-state harmonic analysis technique. This analytical model provides a basis against which simpler reduced order models can be compared. It can also be used to verify the steady-state performance of dynamic models. As the figure shows, the model includes the effects of an unbalanced supply.

4.3 Opportunities in Electrical Network Design

While there exists an extensive range of research fields related to improving the design and performance of IFEP electrical power distribution networks, the AMEPS project focuses on aspects where the interaction with the mechanical systems is a core part. For example, investigations into possible topologies of the electrical network will concentrate on improving the operating conditions of the propulsion drive and prime movers. In particular, attenuating the undesirable interactions between these two systems through the electrical network is an important objective, as doing this will improve the performance of both systems as well as the stability of the system as a whole. Thus, energy storage options and distributed controller configurations will be considered with the integrated system in mind.

Protection and reconfiguration is another aspect of IFEP electrical system design currently receiving significant research attention. Once again the AMEPS project aims to focus on these aspects in consideration of the mechanical systems. For example, it will be important to assess the impact of novel electrical network protection systems on the prime mover operation, and whether any specific electrical transients might cause the gas turbine to perform an emergency shutdown. As described in section 4.1, simulating the extreme operation of the gas turbine is an essential part of protection system design.

To fully study post-fault reconfiguration of the ship's systems it will be necessary to consider the detailed interactions of the prime movers and propulsion drives with the electrical system. Controlling the power electronic drives to the propulsion motors to limit the power drawn may allow fewer loads to be shed during reconfiguration, especially as the propulsion drives form the dominant loads on the electrical network. In addition to this, temporarily relaxing gas turbine temperature limits could allow extra power to be generated through critical times. Representing the drives and prime movers in simpler forms such as power sources and sinks may not provide the required level of functionality to simulate these events though.

One final aspect of interest in the electrical network design is that of coordinated control. Consider the IFEP system delays schematic shown in figure 7. If a torque transient takes place on the propeller, the impact of this on the motor speed will be subject to a time delay due to the effective inertia of the propeller and the rotor. The power electronics drive controller (C_1) will implement corrective action to mitigate any speed variations. This action will cause a change in dc link voltage within the drive, in turn affecting the terminal voltage of the drive, although this too will be subject to a delay as a result of the drive controller and the capacitive and inductive elements of the converter topology. The current lag through the cabling between the propulsion drive bus and the generator bus will effectively delay the arrival of this voltage transient at the generator bus, at which point the generator's AVR (C_2) will take corrective action to restore the bus voltage its nominal level. This corrective action will cause a speed change to the turbine shaft, which will also be subjected to a delay from the effective inertia of the gas turbine and generator rotor. The gas turbine controller (C_3) will seek to adjust the fuel flow to the combustor to regulate this parameter.

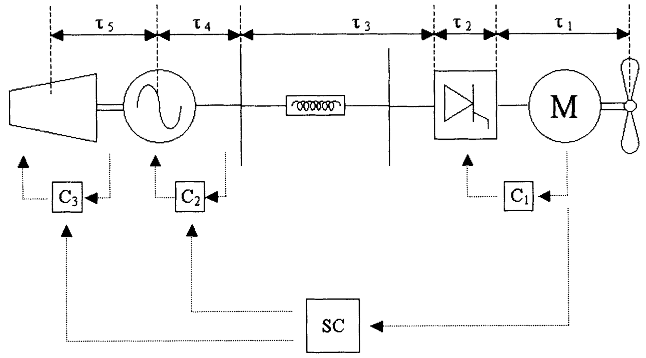


Figure 7: IFEP system delays schematic

Hence, the effects of any torque transients on the propeller are subjected to five system delays plus additional delays from the associated controllers before the fuel flow control system of the gas turbine can react to them. Under some operating conditions, this system could face stability problems as a result of all these system delays, causing controllers to operate in an uncoordinated manner. The development of an integrated model can aid the understanding of such delays as well as the resulting impact of a single event on each part of the system. It should allow improved controller coordination for a faster and more stable system operation. The model could also facilitate studies into a top-level supervisory control (SC) (either centralised or distributed) to improve system stability and effectively bypass many of the system delays by implementing anticipated reaction control to events elsewhere in the system.

5 Conclusions

This paper has reviewed the current research into IFEP systems and has highlighted the need to consider the interactions between the electrical distribution network and mechanical systems in greater detail. The interactions that take place during transients such as crash stops and cyclic propeller loading are key to the design and operation of the individual subsystems. The Advanced Marine Electrical Propulsion Systems project has established a suitable model development methodology to enable effective investigations into the interface behaviour by providing flexibility in model resolution and functionality. This paper gives examples which highlight the potential of the project to thus aid increased understanding of integrated IFEP systems and facilitate improved subsystem design, enhancing the system-level performance.

Acknowledgements

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