A SOLUTION FOR IMPROVED MODELLING EFFICIENCY OF A MULTI-DISCIPLINARY MARINE POWER SYSTEM

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ABSTRACT

Integrated Full Electric Propulsion (IFEP) systems offer increased design flexibility and operational economy by supplying propulsion and service loads from a common electrical system. Predicting the behaviour of IFEP systems through simulation is important in reducing the design risk in a proposed vessel. However the prevalence of power electronics and the potential for interaction between large electrical and mechanical machines introduce significant simulation challenges. This paper presents an integrated IFEP simulation tool, which brings together models from the electrical, mechanical, thermal and hydrodynamic domains, facilitating end-to-end simulation of the behaviour of the propulsion system. This capability enhances the characterisation of modelling interfaces compared to existing tools. The paper discusses the approaches adopted in increasing computational efficiency without unduly compromising the accuracy of simulation results. The model validation process is described, and finally, the paper presents two case studies as an illustration of the phenomena which the model has been used to investigate.

Keywords: all-electric-ship, multi-domain modelling, multi-rate simulation

1. INTRODUCTION

In recent years there has been increasing interest in, and adoption of, Integrated Full Electric Propulsion (IFEP) approaches in both commercial and naval ships. IFEP vessels combine an electric propulsion system with the electric system serving auxiliary and hotel loads into a single common power distribution system (e.g. Hodge and Mattick 1995; Hodge and Mattick 2001; Danan *et al* 2005). This approach is believed to offer a number of benefits, including increased flexibility in the design of vessels, the ability to more closely tailor the engine installation to the vessel's range of duties, and improvements in efficiency, particularly at part load. These benefits may lead to significant financial savings over the lifetime of the ship.

IFEP systems closely integrate a diverse range of electrical and mechanical and hydrodynamic systems through an electrical network with little inertia through which disturbances can propagate very rapidly. Consequently, events in one part of the system, such as an electrical fault, a disturbance at the propeller or simply a sudden change in load, can very quickly have effects on, and provoke responses from, other components. For this reason, improved characterisation of the behaviour of individual IFEP systems is important so that the design of the vessels can be optimised, and to permit effective operation of the ship by the crew, particularly in unusual conditions. Modelling and simulation of IFEP systems, including in particular the inherent interactions between electrical and mechanical systems, is an important element in achieving this objective.

The Advanced Marine Electric Propulsion Systems (AMEPS) consortium, which brings together the expertise of Strathclyde, Manchester and Cranfield Universities, has carried out research to support the development of a high-fidelity simulation tool for electro-mechanical systems, in order to permit the efficient simulation of IFEP systems. The objective of simulations of this type is to obtain a quantified understanding of the interactions between the diverse components through a "whole system" simulation approach (Norman *et al* 2006). Construction of an integrated model within a common simulation environment permits a more complete understanding of system behaviour than could be obtained by analysing each subsystem in isolation.

This paper presents a model of a representative part of an IFEP system which has been constructed by the AMEPS consortium in order to demonstrate the modelling process adopted. Approaches to improve the computational efficiency of the model are outlined, and ways to optimise the balance between efficiency and accuracy are discussed. Model validation is an important consideration in any simulation activity; available methods are reviewed, and the approach adopted in this work is outlined. The paper presents two case studies demonstrating the utility and practical capabilities of the model, thus illustrating the effectiveness of the modeling approach adopted by the consortium.

2. OVERVIEW OF THE AMEPS MODEL

The model developed by the AMEPS consortium (which is shown schematically in Figure 1) brings together three sub-models, each representing a major section of an IFEP system – the electric motor and drive, the power distribution network and the prime mover (in this case, a gas turbine). Each of these models is constructed using the software tools most appropriate for the underlying technology. The motor, drive, propeller and basic hydrodynamics of the ship are modelled using Matlab/Simulink; models of the generator and electrical network, including auxiliary loads and passive filters, are constructed within the SimPowerSystems toolbox of Matlab (Mathworks 2004); and the thermodynamic model of the gas turbine uses FORTRAN code.

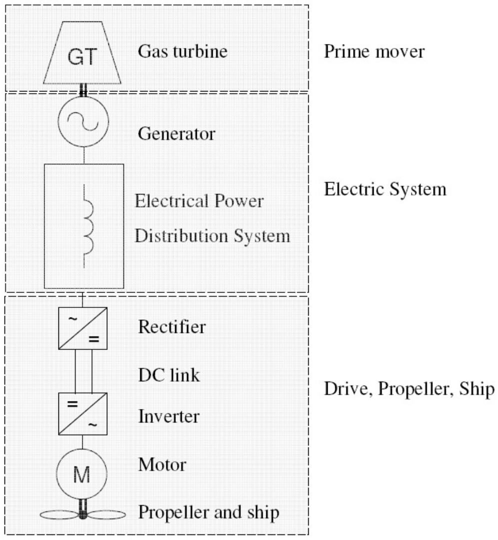


Figure 1: AMEPS Model

The subsystem models were integrated into a single "end-to-end" model within Matlab/Simulink, which permits interconnection of these different modelling approaches. In the following sections, some of the most important challenges of this integration process will be discussed.

3. COMPUTATIONAL EFFICIENCY

A high-fidelity model of a marine IFEP system is necessarily large and complex. Such a model may require significant computational resources in order to carry out simulations, and may consume a significant amount of time to perform each simulation run. Two particular influences on these requirements can be identified (Gole *et al* 1997):

- The level of detail in which typical subsystem models represent the behaviour of equipment may exceed that actually required.
- The need to use short simulation time steps at the same time as simulating events of long duration.

The computational efficiency of the simulation in respect of each of these factors has been optimised as described in the following sections.

3.1. Model Abstraction

When modelling each of the major components within the AMEPS model, and particularly for the faster subsystems such as the power electronic motor drives, care has been taken to model at the minimum acceptable level of fidelity required to fully characterise the phenomena of interest. As well as reducing the computational overhead involved in calculating the state of the model at each simulation time step, this can also enable the use of a larger time step. However, care must also be taken to ensure that this approach does not involve unacceptable approximations or excessive assumptions about overall system behaviour.

For example, the propulsion drive is modelled using a hybrid approach (Apsley *et al* 2007; Gonzalez-Villaseñor, Todd and Barnes 2006) that utilises a detailed diode bridge rectifier model together with an averaged voltage vector inverter model. The use of an averaged rectifier model would also be desirable as this would permit the use of a larger simulation step size for the entire propulsion drive model, further reducing the overall computational burden. However, the switching instants in the diode rectifier are determined by the external circuit conditions on both the AC and DC sides. To predict when these occur, the averaged value model must make assumptions regarding the load current, network voltages and impedances which are not readily applicable to IFEP applications with multi-generator, multi-load power distribution systems. As a result, a detailed diode bridge model, which does not assume fixed network impedances and a balanced supply, has instead been employed.

3.2. Multi-rate simulation

Some components of an IFEP network (such as power electronic converters) experience phenomena which are characterised by very small time constants, of the order of microseconds. As a result, in order to properly characterise these effects and to ensure simulation stability, the time-domain simulation must proceed in very short time steps. For a system of the complexity of an IFEP vessel, this would result in a very large computational burden, which would require significant computing hardware and long simulation times.

It is noticeable, however, that time constants in other parts of the IFEP model are very much longer. Table 1 (Apsley *et al* 2007) shows the wide diversity which may be found in a typical IFEP model.

Table 1. Typical system time constants

Subsystem	Typical Time Constants
Power converter switching	1-5µs
Rotor time constant	50ms – 1s
Propeller run-up time	20s-60s
Ship run-up time	60s-500s

If a common simulation time step were adopted throughout the entire model, computational effort would be unnecessarily expended on high frequency recalculation of the state of elements which only experience slowly varying phenomena. By computing the state of such components less frequently, large efficiencies may be realised.

The AMEPS model implements this concept through a multi-rate simulation approach (e.g. Chen *et al* 2004; Pekarek *et al* 2004; Crosbie *et al* 2007). For each element of the overall model, one of three fixed simulation time steps is selected to satisfy the requirement for adequate characterisation of behaviour without over-simulation. Thus, the gas turbine and propeller-ship models operate with a step size of 1ms, while the main electrical system and propulsion motor models take a 5µs time step to ensure that rapid events such as electrical faults are adequately characterised.

As previously stated, the inverter model adopts an averaged voltage vector behavioural approach to representing the operation of the device. Thus, to capture the averaged switching effects of the converter, a step size of 400µs was selected.

Table 2 shows the practical improvement to the computational efficiency resulting from the use of multi-rate simulation in the AMEPS model in comparison to a single-rate simulation. These results were obtained by averaging the actual elapsed times over multiple simulations of load step events of the indicated “model time” duration.

Table 2: Reductions in simulation time resulting from multi-rate simulation

Simulated event duration (s)	Single rate completion time (s)	Multirate completion time (s)
1	2015	97.4
3	4507	283
5	7970	526

From the results in Table 2 it is observed that the multi-rate simulation is highly beneficial, offering an improvement of up to twenty times in the simulation speed. However, as discussed in the following section, care must be taken to ensure that simulation accuracy is not compromised when simulated values are transported across time-step boundaries.

4. MULTI-RATE SIMULATION VALIDATION

The implementation of a multi-rate simulation has also given rise to new challenges in ensuring that the results do not lose accuracy as a result of transitions between different parts of the model. Two areas of specific interest are addressed in the following subsections.

4.1. Data-transfer Latching

When data is transferred from a part of the model with a short simulation time step into a sub-system with a longer time step, there is a risk that the impact of short-duration, transient phenomena may be inadvertently amplified. To avoid the risk, data transferred must be reflective of the average situation over the longer time step rather than that at the instant of synchronisation (Crosbie *et al* 2007; Pekarek *et al* 2004).

For example, consider a case in which a transient effect of short duration – perhaps a voltage spike lasting for a few time steps – occurs in the behaviour of a component simulated with a short time step, which is adjacent in the model to a component which is simulated with a much longer time step. If the short duration event is taking place at the moment of synchronisation, when data is transferred between the parts of the model, then the slower sub-system may ‘latch’ on to the transient value. That is, while the transient rapidly dies away in the ‘originating’ subsystem, its effects are sustained in the ‘receiving’ subsystem until the next moment of synchronisation.

This phenomenon is illustrated in Figure 2 which shows the transfer of voltage data from the DC-link into the inverter model. The DC-link is in a part of the model which runs at a short time step, whereas the inverter runs at a much longer time step. The graph shows the voltage at the boundary as experienced by the DC-link (grey bars) and the inverter (heavy line). It can be seen from this graph that a short-lived voltage spike at the time of data exchange causes the input to the inverter to ‘latch’ – that is, to behave as if the transient voltage peak was sustained for a much longer time.

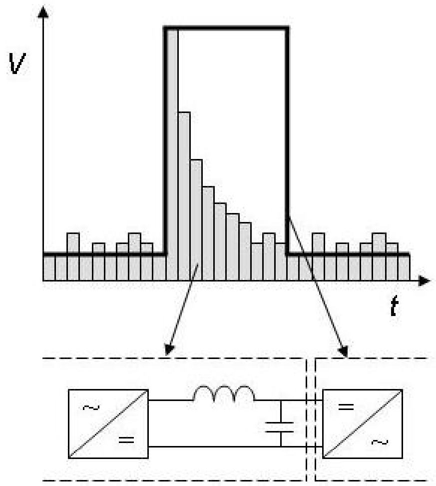


Figure 2: Latching between DC-link and inverter

Given the large time step differences between components in the AMEPS model, this could lead to such transient effects being incorrectly amplified to a significant effect. Some of the events and phenomena which the AMEPS model is intended to investigate, such as electric system faults or sudden load changes in certain parts of the network are likely to lead to problems of this nature, with consequently inaccurate simulation of the behavior of slower-responding components such as the gas turbine.

The AMEPS model uses natural filtering of the data transferred from fast to slow subsystems to reduce the effects of such latching. This approach places the boundaries between different simulation rates in the model at physical boundaries with properties giving inherent resistance to sudden changes in state, such as mechanical inertia or electrical capacitance. Table 3 below lists the fast subsystem to slow subsystem transitions within the AMEPS model and the natural filtering that takes places at each boundary.

Table 3. Natural filtering within the AMEPS model

Fast to slow transition location	Data transferred	Natural filtering aspect
Electrical generator (fast) to gas turbine (slow)	Shaft speed	Shaft and rotor inertia
dc link (fast) to inverter (slow)	Voltage	Inductive and capacitive filter
Propulsion motor (fast) to propeller (slow)	Shaft speed	Motor and propeller inertia

This natural filtering approach is preferable to the addition of explicit filtering or averaging elements at the boundary, since the modelled behavior of and interaction between the adjacent components is not altered. Thus, no artificial sources of error are introduced into the simulation.

Natural filtering has proved satisfactory for all of the simulations conducted to date using the AMEPS model. However it is recognised that where disturbances close to a naturally-filtered boundary are introduced, conflicts may arise between the averaging behavior of the boundary and its interaction with the disturbance. For example, if an electrical fault is simulated in the DC link or inverter, then the interaction between the fault and the inductive and capacitive elements will nullify their filtering effects. Indeed the transient current and voltage effects induced by this interaction may exacerbate the latching problem at this boundary.

In such cases, the introduction of artificial low-pass filtering elements can be considered in order to reduce simulation inaccuracy in the slower subsystem. However, the error introduced by this addition should be balanced against that resulting from the data latching effect to ensure that the lowest possible overall error is achieved.

If it is not possible to balance added filtering against latching to give an acceptable level of overall error, then the simulation time step of the slower subsystem at the boundary can be shortened. This will reduce the error by synchronizing the fast and slow sides of the boundary more frequently, at the cost of longer simulation times.

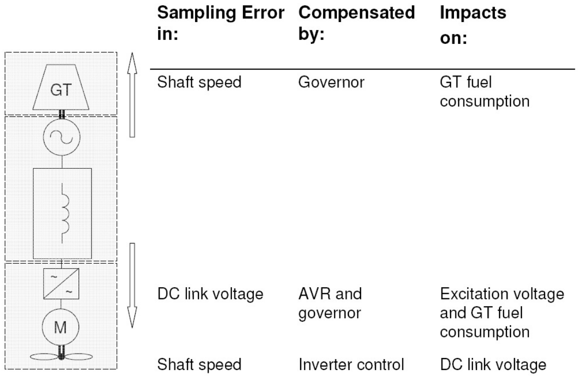
The assessment of the overall effect of these errors on simulation accuracy is not a straightforward task, since it will involve the evaluation of the propagation of the error through other subsystems which are connected to those at the time step boundary. As a result the accuracy of results emanating from those subsystems may be affected; this issue is discussed in more detail in the following section. The existence of closed loop control systems complicates the task further, since the combination of sampling and filtering processes involved may have the effect of compensating for the error, producing an output signal which is close to the ‘correct’ result without the effect of the error. For example, the propulsion drive controller will attempt to achieve the desired propeller speed with an erroneous DC link voltage, as it would with the ‘true’ voltage. Although the response of the controller will be different in the two cases, the end result – the propeller speed – may be near-identical. This assumes of course, that the magnitude of the error is not such that it alone drives the controller or the controlled devices into saturation. Therefore, benign controller behaviour as described here cannot be assumed, and careful consideration must be given to the effects of the different controller response on other subsystems.

4.2. Model Error Propagation

In the case discussed above, the controller response prevents errors in the DC link voltage from propagating into the propeller behaviour. However, this will result in the current drawn from the rectifier differing from the “error-free” case. This current variation will disrupt current flows in the remainder of the network, with corresponding disturbance to voltages. Other controllers elsewhere in the system will have their behaviour changed by these variations, which will ultimately alter the response of the generator and the gas turbine. Thus, errors resulting from sampling and filtering in one subsystem within the model can propagate both upstream and downstream in the model – in a similar way to genuine disturbances – and as such, result in inaccuracies in the results generated in other subsystems.

Specifically, the presence of closed loop controllers tends to permit all simulation based errors to propagate back to the field voltage of the generator and to the fuel flow into the gas turbine. These quantities have no further upstream influences and constraints unlike, for example, the gas turbine speed which is influenced by the fuel flow and generator load. Figure 3 below identifies examples of compensation of synchronization errors by controllers, and the wider impact of this compensation.

This paper has already shown that multi-rate simulation is a very effective means of controlling the length of time and level of computing resources required to simulate a marine electrical system. In many cases, it may be vital to the ability to simulate events of realistic duration without resorting to unacceptable model simplification. Nonetheless, as discussed here, it is necessary to take care to understand the implications for model accuracy when applying the approach. Multi-rate simulation also presents challenges for the validation of models, as will be discussed in the next section.



Sampling Error in:	Compensated by:	Impacts on:
Shaft speed	Governor	GT fuel consumption
DC link voltage	AVR and governor	Excitation voltage and GT fuel consumption
Shaft speed	Inverter control	DC link voltage

Figure 3: Error propagation

5. VALIDATION OF AMEPS MODEL

When constructing and using a simulation model, it is important to consider how its validity can be tested and evaluated. In this section of the paper, the selection and application of validation methods to the AMEPS model is discussed.

5.1. Validation

Law (2005) defines validation of a model as a process to determine whether the model is an acceptably accurate representation of the system with in the context the objectives of the study in which it is applied. A model should be designed and developed to address one or more questions which are understood in advance; this also specifies the level of detail required in the model (Law 2005; Sargent 2003).

5.2. Validation Methods

Sargent (2003) describes a number of methods which can be used to assess the validity of a model. Examples include:

- *Face validation*: In this approach, opinions are sought from one or more experts as to the acceptability of the model's construction and/or the behaviour it predicts.
- *Comparison to other models*: The simulation results of the model to be validated are compared with the results of other previously-validated or independently constructed models.
- *Predictive validation*: In this method, simulation results are compared against measurements made in the field obtained by experiment.

Commonly, a number of validation methods would be employed together to provide greater levels of confidence.

5.3. Subsystem Validation of the AMEPS Model

The hybrid propulsion drive subsystem of the AMEPS model has been validated using the *comparison to other models* approach. The hybrid model was compared against an equivalent model constructed using the PLECS piecewise linear element circuit simulation tool (Plexim GmbH 2008). The validation was carried out using time plots of the line-line supply voltages and line currents produced from the hybrid and PLECS models. In both cases, simplified electrical supply and propeller models were used to permit validation in isolation from the remainder of the AMEPS model.

Additionally, *predictive validation* was applied to the motor model. A variety of tests were carried out on a multi-phase induction motor test rig (Apsley *et al* 2007). The test conditions were replicated in the AMEPS motor model and the actual and simulated behaviour compared. Figure 4 shows an example of this comparison, in which the rotational speed of the real and simulated motors are shown when a ramp change in flux current is applied, followed by a step change in torque current. Figure 4 demonstrates the accuracy of the motor model.

A similar approach has been adopted in validating the gas turbine model, for which manufacturer's performance curves have been used as a basis for comparison. *Face validation* of aspects of the dynamic behaviour of the gas turbine was also used.

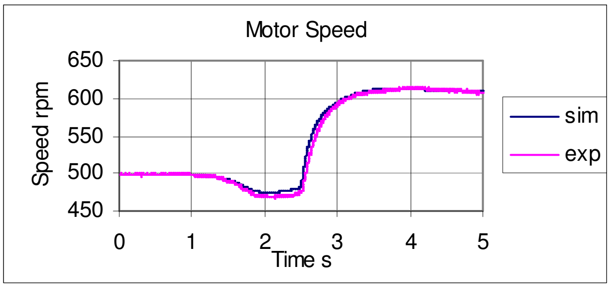


Figure 4: A comparison of experimental and simulation motor speed

The propeller model was validated both by *comparison to other models*, which was useful in validating the implementation of the model, and through *face validation*, in which assistance from domain experts in industry was obtained. This assistance was particularly valuable in validating the underlying mathematical assumptions, and in interpreting the results generated.

Models of electrical network components were mainly validated using *face validation*. In future work, further validation using other approaches, notably the use of hardware-in-the-loop simulation approaches (Palla *et al* 2007) to permit *predictive validation* of component models in the context of a complete network, may be pursued to increase confidence in the validity of the models.

5.4. System Level Validation

As described previously, a number of methods are available for validation of the individual subsystems making up the AMEPS model. Although a set of validated subsystem models might be expected to result in an accurate whole system model, experience has shown that the complexity of the interactions between subsystems, and the risk of incompatible validation assumptions can lead to non-trivial emergent behaviour, suggesting that additional validation would be beneficial.

In principle, the validation methods applied to the subsystems are equally applicable to the validation of the integrated model. In practice, however, a number of difficulties arise. Consider, for example, the question of determining the effect of data latching errors introduced by the multi-rate simulation approach.

Naïvely, it might be assumed that the *comparison to other models* approach could be applied by simply comparing results from the multi-rate model with those from a model entirely simulated at the smallest simulation step size. This would permit straightforward quantification of the overall effect of these errors. However, as discussed above, simulation of many conditions for which the model would need to be validated – for example propeller events – would have impractical requirements of time and computing resources without multi-rate simulation. Therefore, although this validation method has some applicability, other approaches are also needed, particularly as the size and complexity of the integrated model increase.

Predictive validation of the model using field data obtained from IFEP vessels is also attractive. However, detailed data relating to existing vessels is difficult to obtain as a result of confidentiality issues. It is also of limited utility in validating models of vessels which are at the design stage or under construction. Considering that an important benefit of "whole system" simulation is to reduce design risk, this is an important drawback. Construction of a hardware test rig such as the Electric Ship Technology Demonstrator (Mattick *et al* 2005; Danan *et al* 2005) might be an alternative, but is very costly and negates many of the economic benefits of using simulation to de-risk vessels at the design stage. The range of equipment and configuration options which could be investigated is also limited in this approach.

As an alternative, model accreditation (DMSC 2006) was used as a means to assess the validity of the results produced by the integrated AMEPS model. In this process, *face validation* has been carried out by domain experts on simulation results obtained from each subsystem when integrated within the complete model. Although it is recognised that *face validation* is an inherently subjective approach, this is perhaps the best practically achievable solution in the light of the limitations discussed above. It is clear, however, that there is a need to develop a robust framework within which the integrated model can be further validated. This appears particularly important since, as discussed elsewhere in this paper, the level of accuracy in the simulation results may vary according to the scenario being simulated.

6. SIMULATION CASE STUDIES

This section will demonstrate the capabilities of the AMEPS model by presenting two case studies. The first case study assesses the system behaviour after a sudden loss of the propulsion load (caused by a protective trip mechanism within the power electronic motor drive). The second case study assesses the effect of a cyclic propeller loading on the electrical network and prime mover behaviour.

6.1. Model Description

These case studies consider the power distribution network shown in Figure 5, which is similar to one possible operational configuration of the Type 45 Destroyer (Norton and Saxby 2006).

The MV and LV voltage levels are 4160VAC and 440VAC respectively. The gas turbine and propulsion motor are rated at 21MW and 20MW respectively. The MV and LV loads are rated at 2.5MVA and 0.5 MVA respectively with a power factor of 0.85.

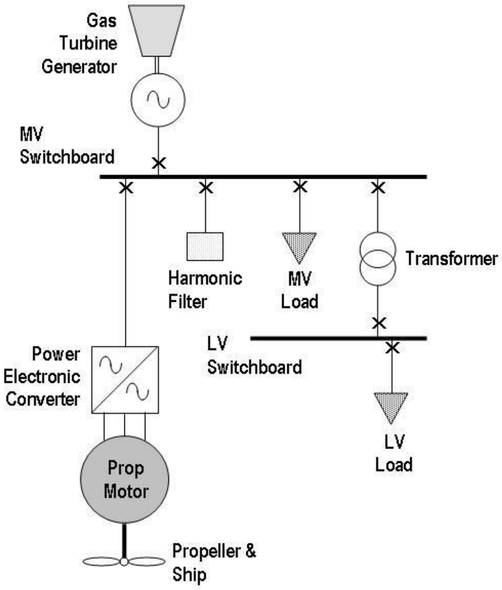


Figure 5: Type 45 single-line diagram

Figure 6 shows the vessel speed control loop. This is a cascade controller where V_s is the vessel speed, ω the AIM speed, Q^* the AIM reference torque and T the propeller thrust. In this case V_s^* is set to 10 m/s, which is kept constant by adjusting Q^* . The propeller is modelled using the Wageningen-B series (Apsley *et al* 2007).

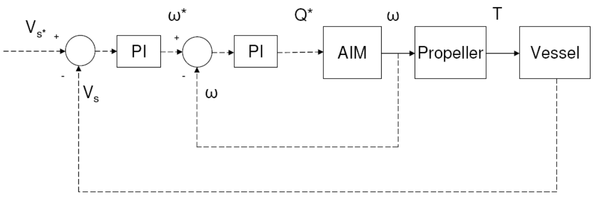


Figure 6: Vessel Speed Control Loop

6.2. Sudden loss of Propulsion Load

This particular scenario investigates the overall system behaviour under severe operating conditions in which the power drawn by the propulsion motor instantaneously drops from the nominal level at cruising speed to zero after 0.5 seconds of simulation time (representing a trip event within the main propulsion drive). Figures 7 to 11 show the simulation results for this scenario.

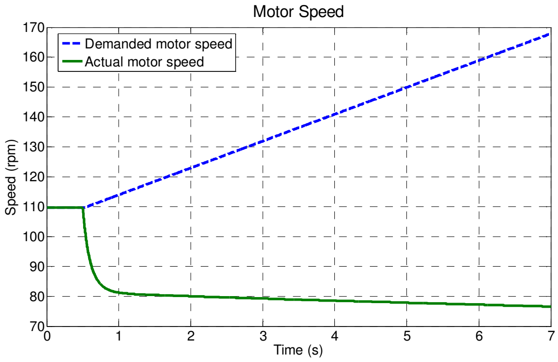


Figure 7: Propulsion Motor Speed

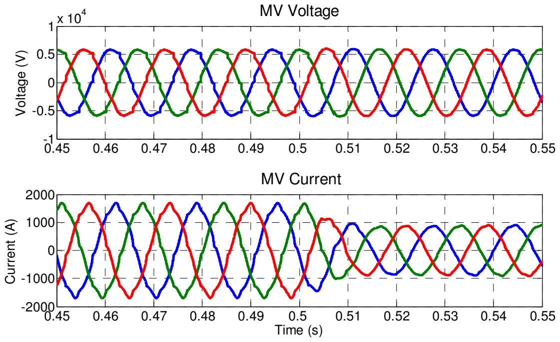


Figure 8: MV Voltage and Generator Current

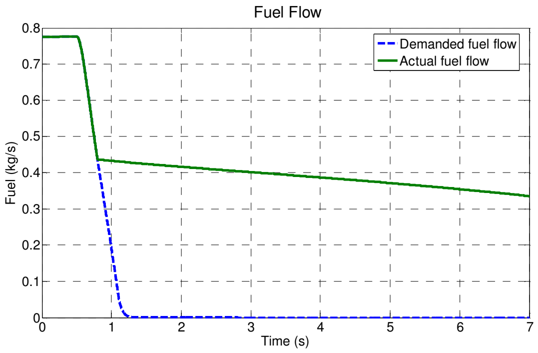


Figure 9: Gas Turbine Fuel Flow

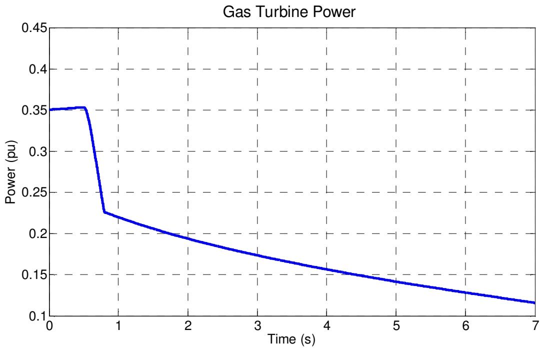


Figure 10: Gas Turbine Power

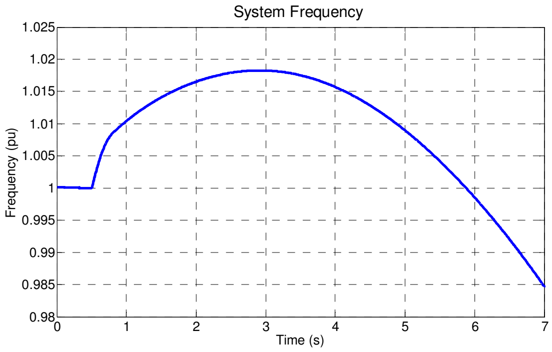


Figure 11: System Frequency

Figure 7 shows a trace of the desired (dotted trace) and actual (solid trace) propulsion motor speed. In this figure the demanded motor speed increases in response to the dwindling vessel speed (not shown). However, the actual motor speed begins to decline following the converter trip as all power to the propulsion drive is lost.

The three-phase MV voltage and current traces (measured at the terminals of the generators) are shown in Figure 8. Note that these traces are shown over a much shorter time frame than the other the parameters presented in order to highlight the waveform distortion evident in these quantities. Prior to the loss of propulsion load, distortion resulting from the operation of the diode bridge rectifier is evident in both traces. Following the loss of propulsion load, however, there is a notable reduction of harmonic content in both traces as the diode bridge ceases to draw any significant power from the main network.

Figure 9 shows the demanded (dotted line) and actual (solid line) gas turbine fuel flow. Immediately after the sudden loss of the propulsion load, there is a surplus of power delivered by the gas turbine. As the gas turbine governor tries to maintain the system frequency at a constant value, it rapidly decreases the fuel flow demand to the minimum level. However, in order to prevent damage to the gas turbine, the rate of change for the actual fuel flow is limited by internal controllers. This limiting action is evident in the plot of actual fuel flow in Figure 9. This in turn causes the power output of the gas turbine (Figure 10) to decrease at a much slower rate than desired by the governor control. As a result, a significant transient in network frequency occurs while the output power of the gas turbine adjusts to the new network loading conditions (Figure 11).

6.2.1. Discussion of Results

This first case study is an excellent illustration of the potential interactions that can take place within IFEP power systems. It clearly illustrates how response of one subsystem to a transient in a separate location can have a substantial impact on the remainder of the power system. Non-linear effects in the gas turbine control have caused exaggerated swings in the network frequency and a particularly poor system response to the original perturbation. Degraded power quality is thus being provided for the remainder of the loads connected to the network. This may have further undesirable consequences, such as nuisance tripping of sensitive loads. An improved control scheme for the gas turbine might be devised, balancing the protection of the prime mover against transients with the effects on the wider IFEP system. This approach may improve the overall system response, although it appears that the initial frequency rise may still be unavoidable, thus preventing a rapid network recovery.

Instead, adopting a coordinated control approach may have a greater impact on mitigating the effects of the propulsion system transient. In this manner, knowing the limitations of the gas turbine in dealing with the loss of load, additional systems within the network (smaller prime movers, electrical loading and energy storage) could be operated more effectively to complement its actions and improve the overall system response to the transient. In this way, a coordinated control approach could provide a substantial increase in functionality over that of isolated control systems.

6.3. Propeller Cyclic Loading

This case study demonstrates the effect of cyclic propeller loading on the entire IFEP system. Such loading can be a result of a vessel cruising in heavy seas where propeller emergence and 'slamming' often occurs. In this case study, a simplified cyclic sinusoidal propeller loading profile with a frequency of 0.1Hz and a magnitude of 10% rated thrust has been applied (initiated from 0.5 seconds of simulation time) to illustrate the effects of such loading. Note that this propeller loading profile is in line with the range of realistic values given in (Stewart 2005).

Figures 12 to 16 illustrate the simulation results for this case study.

6.3.1. Discussion of Results

The effect of the cyclic loading can clearly be observed in Figures 12 to 16. In contrast to the previous case study, there is no control saturation present within the gas turbine in this mode of operation, and as such, the actual fuel flow is the same as the demanded fuel flow (Figure 13).

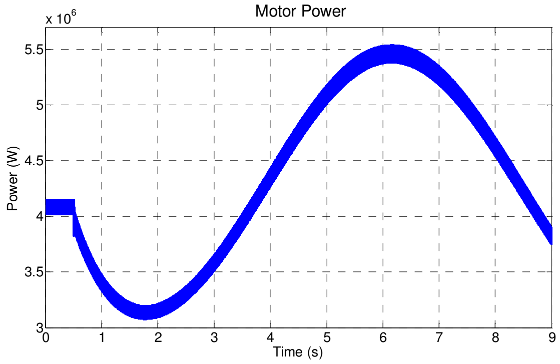


Figure 12: Motor Power

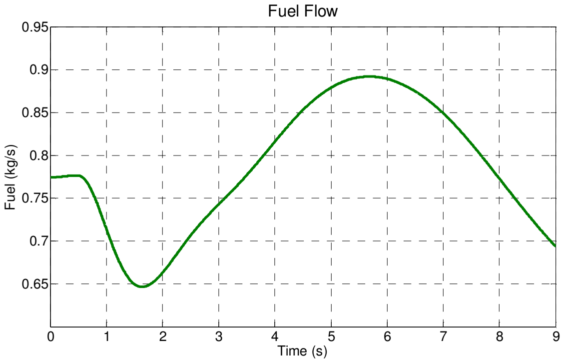


Figure 13: Gas Turbine Fuel Flow

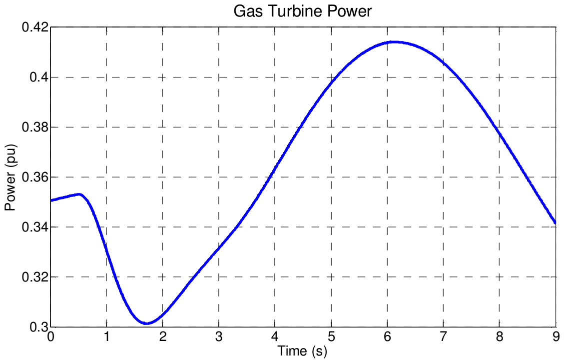


Figure 14: Gas Turbine Power

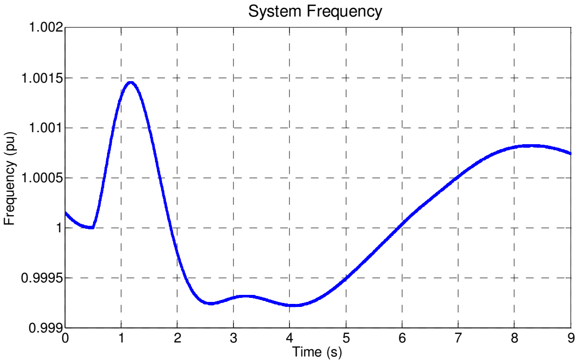


Figure 15: System Frequency

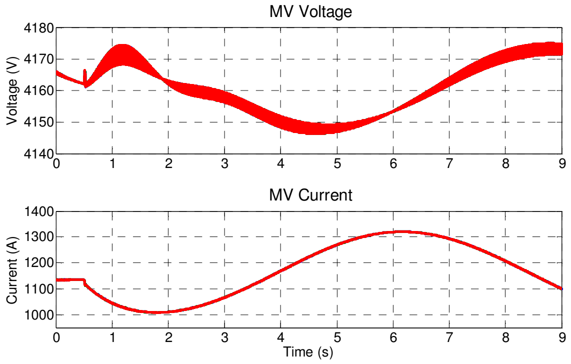


Figure 16: RMS Busbar Voltage and Generator Current

As a result of this behaviour, the response of the gas turbine is sufficient to maintain the network voltage and frequency within acceptable limits despite substantial variation in the magnitude of the network loading.

However, it should be noted that in reality, sea waves do not subject the propulsion systems to a single frequency disturbance but are composed of a range of frequencies (Stewart 2005). The response of the propulsion system to these different disturbance frequencies will vary and this may result in a far greater impact on the prime mover operation and network frequency than that presented here (Elders *et al* 2008). As such, the authors intend to extend the work presented here to consider the impact of a wider range of cyclic loading effects.

7. CONCLUSION

This paper has presented a model developed by the AMEPS consortium to demonstrate the holistic modelling of electrical and mechanical subsystems of an IFEP vessel's propulsion system. Some of the major modelling challenges which have been encountered were identified, and approaches to overcome them discussed. Multi-rate simulation was shown to be a highly effective means of improving the computational efficiency of the model and for reducing the time required for simulations. However, there is a risk that transfer of information between parts of the model simulated at different rates approach may introduce inaccuracies; means for controlling these errors have been discussed in this paper. Validation of simulation models is important in assuring the reliability of the results they produce. A variety of methods have been used to validate the AMEPS model; however only model accreditation can be said to be viable at present as a means of validating the integrated AMEPS model as a whole. Further research into the validation of large and complex models is desirable.

Finally, the case studies presented in the paper demonstrate the capabilities of integrated electrical-mechanical simulation models such as the AMEPS model in assessing the behaviour of IFEP systems when subjected to external events. In an industrial context, this capability will be valuable in, for example, determining compliance with classification society rules.

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