De-risking Integrated Full Electric Propulsion (IFEP) vessels using advanced modelling and simulation techniques

by

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Declaration of Authenticity and Author's Rights

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination, which has led to the award of a degree.

Signed: J.D. Schuddebeurs

Date: November 2014

Untuk semua orang yang saya cintai

(For everyone I love)

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Without the support of my family, I would never have completed my thesis. Words cannot express how grateful I am to my parents Peter and Tjitske for their support and never-ending believe in me during all those years. Also, I would like to thank my brother George, my sister Mirjam and my friends for their support and faith in me. Last but not least, I would like to thank my wife Femke for her understanding and love during the past few years.

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Nomenclature

Abbreviations

AES	All Electric Ship
AMEPS	Advanced Marine Electric Propulsion Systems
CPP	Controllable Pitch Propeller
DEF STAN	Defence Standard
DNV	Det Norske Veritas
DP	Dynamic Positioning
EPSRC	Engineering and Physical Sciences Researchers Council
EMALS	Electromagnetic Aircraft Launch System
EM	Electromagnetic rail gun
EMTP	Electromagnetic Transients Programme
ES	Energy Storage
ESTD	Electric Ship Technology Demonstrator
FPP	Fixed Pitch Propeller
GTE	Global Truncation Error
HVAC	Heating Ventilation Air Conditioning
IEEE	Institute of Electrical and Electronics Engineers
IFEP	Integrated Full Electric Propulsion
LNG	Liquefied Natural Gas

LR	Lloyds Register
LTE	Local Truncation Error
LV	Low Voltage
MV	Medium Voltage
ODE	Ordinary Differential Equation
OOM	Object Oriented Model
OSV	Offshore Supply Vessel
PT	Power Turbine
PTE	Propagated Truncation Error
SME	Subject matter expert
SOLAS	Safety of Life at Sea
SPS	SimPowerSystems™
STANAG	Standardization Agreement
VV&A	Verification Validation and Accreditation

Abstract

Complex multi-domain engineering systems, where for example mechanical and thermal (sub)systems are connected to each other in some way, have increasingly become a vital part of our society. An example of such a system is the Integrated Full Electric Propulsion (IFEP) concept for the marine shipping industry. With this IFEP concept, as opposed to the more conventional marine power system, the power for the ship's propulsion and ship's services is provided by a common power plant. This offers advantages including fuel efficiency and design flexibility. However, due to its system complexity and capital costs, it is important that the overall dynamic behaviour of these systems can be predicted in the early stages of the design. Predicting the overall system behaviour can be obtained by employing an integrated end-to-end model, which combines detailed models of for example the mechanical and electrical (sub)systems. This allows for example ship designers to investigate disturbances and the primary and higher order responses across the system. However, present existing simulation tools do not easily facilitate such employment of a holistic approach.

In this thesis the focus is on how advanced modelling and simulation techniques can be used to de-risk the design and in-service of complex IFEP systems. The state–of-the-art modelling and simulation techniques as well as the IFEP application area are considered.

An integrated-model of an IFEP vessel was developed under the EPSRC collaborative AMEPS (Advanced Marine Electric Propulsion System) research project, which forms a major part of this thesis. In order to reduce the computational burden, due to a wide variety of time constants in the IFEP system, a multi-rate simulation technique was proposed. It was demonstrated that a reduction in simulation execution time between 10-15 times can be achieved. However, it was conceptually argued that multi-rate simulation could introduce errors, which propagates itself across the system thereby provoking potential unrealistic responses from other subsystems. Several case studies were conducted based on this model, which shows that such an integrated end-to-end model may be a valuable decision-support tool for de-risking the design and in-service phases of IFEP vessels. For example, it was demonstrated that a disturbance on the propeller could provoke a saturation of the gas turbine governor.

Different power system architectures were proposed for IFEP power systems such as radial and hybrid AC/DC. For this thesis, an initial study was conducted to assess the relationship between the type of power system architecture and the vessel survivability. For this assessment an existing vessel survivability theory was further developed into a quantitative method. It was concluded that based on a comparative short circuit study and the proposed survivability method that the IFEP-hybrid AC/DC architecture offers the best vessel survivability.

Chapter 1 Introduction

1.1 Overview

This thesis comprises two main but distinct complementary parts. The first part (chapter 2 and 3) focuses on challenges and solutions related to Integrated Full Electric Propulsion (IFEP) technology and the modelling of complex multi-domain[1] systems. The second part (chapter 4 and 5) focuses on the holistic system behaviour and electrical network architecture design considerations of IFEP vessels[2]. The second part is supported by theory, discussions and models, which have been developed and described in the first part.

The work described in this thesis was conducted under an EPSRC-funded research project called Advanced Marine Electric Propulsion Systems (AMEPS) [e.g. Norman06b].

1.2 Motivation and research justification

With increasing concerns over global warming, there is a high priority within the transport sector to reduce greenhouse gas emissions. Greenhouse gas emissions from shipping are increasing at a significant rate due to the rapid growth in global shipping. In terms of CO_2 emission the International Maritime Organisation (IMO) suggests that the global shipping is presently responsible for approximately 1Gt CO_2 (about 3.3% of total global CO_2

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[1] A combination of at least two different physical domains, which could include the following domains: mechanical, electrical and thermal.

[2] In this thesis the words “vessel” and “ship”are interchangeable.

emission). Predictions for 2050 suggest that by then the global shipping CO_2 emission could be in the range of 2.4-3.6Gt CO_2 [CCC08]. Clearly, there is a need to assess the technological possibilities to reduce emissions (not only CO_2 but also NO_X and SO_X [Nikopoulou08]) produced by the marine shipping industry. The IFEP concept has been the subject of increased interest across commercial and naval shipping industries for over two decades as this offers a number of benefits including reduced emissions [e.g. Ådanes03, Kanellos12, and Doerry13].

As opposed to more conventional power systems on board ships, IFEP provides both the ship's propulsion and other electrical services with electrical power from a common set of prime movers. Additional IFEP benefits include design and operational flexibility [e.g. Hodge95, Newell99, Little03 and Ådanes03]. Examples of IFEP ships are the RMS Queen Mary II [ShipTechnology08] and the HMS Daring (Type 45 Daring Class Destroyer, Royal Navy) [BAESystems08].

IFEP can be characterised as a power dense system with relatively large loads, limited cable impedances and system inertia. Therefore disturbances, such as mechanical and electrical faults, can easily propagate across the entire power system and hence cross physical domains and subsystems (e.g. prime movers, electrical motors, and generators). As a consequence, subsystem controllers react to these disturbances, thereby often affecting the performance of the overall power system. These complex domain/subsystem interactions may jeopardise the power system stability and hence power system availability and vessel survivability. This is particularly true under certain critical harsh operating conditions, such as battle and Dynamic

Positioning (DP[3]) in heavy seas. In order to de-risk the design and in-service of these vessels, a tool is required, which helps to predict the overall power system behaviour. As the various interactions between the several subsystems need to be analysed as well, considering subsystems in isolation will not be sufficient. Therefore an integrated end-to-end simulation model (hereafter termed "integrated-model"), representing the complex multi-domain nature of IFEP vessels, is required. However, presently there is a lack of modelling and simulation tools that support such an integrated-model approach.

1.3 Objective and research questions

Based on the problem definition of Section 1.2, the general objective of this thesis can be defined as:

Investigate what modelling and simulation techniques are required in order to efficiently de-risk the design and in-service of complex IFEP vessel and to investigate how the vessel survivability is affected by the IFEP architecture.

In order to structure the thesis around this research objective, three main research questions were formulated, which are:

- Research Question 1 How can complex multi-domain systems best be modelled and simulated while taking into account the required level of model fidelity and the multiple time constants present within these physical domains and subsystem?

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[3] DP is a mode of operation whereby the vessel keeps automatically a predefined position and heading using its propulsion and manoeuvreing systems.

- Research Question 2 How can a model, which meets the requirements of Research Question 1, be applied to de-risk the design and in-service of IFEP vessels?
- Research Question 3 How does the architecture of IFEP power systems in general affect the power availability and hence vessel survivability?

1.4 Thesis contributions

The contributions of this thesis to the research community are listed in short below.

- **Guidelines on advanced modelling and simulation:** Comprehensive guidelines on modelling and simulation of complex high-fidelity multi-domain systems were developed.
- **Insights into multi-rate error propagation:** A robust approach was developed in which the error propagation, due to multi-rate simulation in complex multi-domain systems, is described. The focus here is not on errors arising from the mathematical algorithms but on errors arising from the feedback loops in the model. This approach also includes solutions to reduce the error.
- **Advanced integrated IFEP vessel model:** Several high-fidelity submodels, such as a gas turbine and electric drive submodel, were successfully connected to each other. This has resulted in a modelling and simulation platform; useful for de-risking the design and in-service of complex multi-domain IFEP systems.
- **Novel approach to quantify vessel survivability:** An existing theory about vessel survivability was applied and mathematically further developed – thereby providing a quantitative method to compare vessel survivability of different IFEP architectures.

1.5 Thesis outline

This thesis has been divided in 6 main chapters. A brief overview of each of the chapters 2 -6 will be given below.

- *Chapter 2* The objective of this chapter is to provide an insight in the development, the advantages and disadvantages of the IFEP concept onboard vessels. In addition a number of related key research challenges will be discussed.
- *Chapter 3* Predicting the behaviour of complex multi-domain systems (such as IFEP) requires an integrated simulation model. A number of research challenges and possible solutions, including model causality and varying time constants, related to the development of such a model will be discussed in this chapter. For example a critical qualitative review of multi-rate simulation techniques, a technique to reduce the computational burden is presented in this chapter.
- *Chapter 4* An integrated-model of a typical IFEP system was developed under the AMEPS project and will be presented in this chapter (also referred to as "AMEPS model" in this thesis). The AMEPS model was subjected to a number of case studies, such as the instantaneous loss-of-propulsion load, in order to provide a better insight in the overall system behaviour. These case studies will be presented in this chapter as well.
- *Chapter 5* A quantitative comparison between a number of different IFEP power system architecture philosophies will be presented in this chapter. In particular the power system performance of these architectures under severe operating conditions, such as short circuits, has been considered.

- *Chapter 6* This chapter presents the thesis conclusions and future research work

1.6 Associated publications

Several publications, both first author and co-author, have been produced during the research reported in this thesis. These publications are:

- **Schuddebeurs, J.D.,** Norman, P.J., Elders, I.M., Galloway, S.J., Booth, C.D., Burt, G.M. and Apsley, J.M., (2010) A solution for improved simulation efficiency of a multi-domain marine power system model. *International Journal of Simulation and Process Modelling (IJSPM)*, 6(1), pp.67-77.
- Apsley, J.M., Gonzales Villasenor, A., Barnes, M., Smith, A.C., Williamson, S., **Schuddebeurs, J.D.**, Norman, P.J., Booth, C.D., Burt, G.M. and McDonald, J.R., (2009) Propulsion drive models for full electric marine propulsion systems. *IEEE Transactions on Industry Applications*, 45(2), pp.676-684.
- Booth, C.D., Elders, I.M., **Schuddebeurs, J.D.**, McDonald, J.R. and Loddick, S., (2008) Power system protection for more and full electric marine systems. *IMarEST Journal of Marine Design and Operation*, Part B13, pp.37-45.
- **Schuddebeurs, J.D.**, Norman, P.J., Elders, I.M., Galloway, S.J., Booth, C.D., Burt, G.M. and Apsley, J.M., (2008) A solution for an improved modelling efficiency of a multi-disciplinary marine power system. *20th European Modeling and Simulation Symposium (EMSS2008).* Campora San Giovanni, Italy 17-19 September 2008.
- **Schuddebeurs, J.D.**, Norman, P.J., Booth, C.D., Burt, G.M., McDonald, J.R., Apsley, J. and Gonzalez Villasenor, A., (2008) A holistic system

modelling approach for marine power systems. *16th Power Systems Computation Conference (PSCC2008)*. Glasgow, UK 14-18 July 2008.

- **Schuddebeurs, J.D.,** Norman P.J., Galloway, S.J., Burt, G.M., McDonald, J.R. and Apsley J., (2008) A high-fidelity integrated system model for marine power systems. *In: IEEE, 2nd International Systems Conference. Montreal,* Canada 7-10 April 2008.
- Apsley, J.M., Todd, R., Barnes, M., **Schuddebeurs, J.D.** and Careme, S., (2008) Experimental validation of load disturbances on a multiphase marine propulsion drive model. *In: IET, 4th Power Electronics, Machines and Drives (PEMD2008).* York, UK 2-4 April 2008.
- Elders, I.M., **Schuddebeurs, J.D.**, Booth, C.D., Burt, G.M., McDonald, J.R. and McCarthy, J., (2008) Energy storage systems as a mechanism for improving power quality in an IFEP system. *In: IMarEST, 9th International Naval Engineering Conference (INEC2008)*. Hamburg, Germany 1-3 April 2008.
- Booth, C.D., Elders, I.M., Mackay, A., **Schuddebeurs, J.D**. and McDonald, J.R., (2008) Power system protection of all electric marine systems. *In: IET, 9th Developments in Power System Protection (DPSP2008),* Glasgow, UK 17-20 March 2008.
- **Schuddebeurs, J.D.**, Elders, I.M., Booth, C.D., Burt, G.M. and McDonald, J.R., (2007) IFEP power system fault and network architectures comparison studies for vessel survivability assessment. *In: IMarEST and SEE, All Electric Ship (AES2007).* London, UK 25-26 September 2007.
- **Schuddebeurs, J.D.**, Norman, P.J., Booth, C.D., Galloway, S.J., Burt, G.M., McDonald, J.R., Apsley, J., Gonzalez Villasenor, A., Barnes, M., Smith, A.C., Williamson, S., Mody, B., Kyritsis, V., Pilidis, P. and Singh, R., (2007) Investigations into electrical-mechanical interactions

within IFEP systems using a holistic simulation tool. *In: IMarEST and SEE, All Electric Ship (AES2007).* London, UK 25-26 September 2007.

- Apsley, J.M., Gonzalez Villasenor, A., Barnes, M., Smith, A.C., Williamson, S., **Schuddebeurs, J.D**., Norman, P.J., Booth, C.D., Burt, G.M. and McDonald, J.R., (2007) Evaluation of reverse power flow in electric propulsion drives. *In: IMarEST and SEE, All Electric Ship (AES2007)*. London, UK 25-26 September 2007.
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- **Schuddebeurs, J.D**., Booth, C.D., Burt, G.M. and McDonald, J.R., (2007) Impact of marine power system architectures on IFEP vessel availability and survivability. *In: IEEE, Electric Ship Technologies Symposium (ESTS2007)*. Arlington, US 21-23 May 2007.
- Elders, I.M., Norman, P.J., **Schuddebeurs, J.D**., Booth, C.D., Burt, G.M., McDonald, J.R., Apsley, J., Barnes, M., Smith, A., Williamson, S., Loddick, S. and Myers, I., (2007) Modelling and analysis of electro-mechanical interactions between prime-mover and load in a marine IFEP system. *In: IEEE, Electric Ship Technologies Symposium (ESTS2007).* Arlington, US 21-23 May 2007.
- Apsley, J.M., Gonzalez Villasenor, A., Barnes, M., Smith, A. C., Williamson, S., **Schuddebeurs, J.D**., Norman, P. J., Booth, C. D., Burt, G.M. and McDonald, J. R., (2007) Propulsion drive models for full electric marine propulsion systems. *In: IEEE, International Electric Machines and Drives Conference (IEMDC07)*. Antalya, Turkey May 3-5 2007.

- **Schuddebeurs, J.D.**, Norman, P.J., Booth, C.D., Burt, G.M. and McDonald, J.R., (2006) Emerging research issues regarding Integrated-Full Electric-Propulsion. *41st International Universities Power Engineering Conference (UPEC2006)*. Newcastle upon Tyne, UK 6-8 September 2006.
- Norman, P.J., Booth, C.D., **Schuddebeurs, J.D.**, Burt, G.M., McDonald, J.R., Apsley, J.M., Barnes, M., Smith, A.C., Williamson, S., Tsoudis, E., Pilidis, P. and Singh, R., (2006) Integrated electrical and mechanical modelling of Integrated-Full-Electric-Propulsion systems. *In: IET, 3rd Power Electronics Machines and Drives (PEMD2006)*. Dublin, Ireland 4-6 April 2006.
- Norman, P.J., **Schuddebeurs, J.D.**, Booth, C.D., Galloway, S.J., Burt, G.M., McDonald, J.R, Villasenor, A., Todd, R., Apsley, J.M., Barnes, M., Smith, A.C., Williamson, S., Mody, B., Tsoudis, E., Pilidis, P. and Singh, R., (2006) Simulating IFEP systems. *IMarEST Marine Engineering Review (MER)*, October 2006, pp.26-31.

Chapter 2 Integrated Full Electric Propulsion – an overview

2.1 Chapter overview

In this chapter the main drivers, concepts and key research challenges of IFEP systems will be discussed. Important generic principles on marine power systems will be reviewed first.

2.2 Definitions for conventional and (future) IFEP/AES vessels

2.2.1 System functionalities

It is important to understand the operational profile or mission of a vessel as this determines what kind of power system is required on board. Typical missions include the transport of containers on intercontinental routes, bringing fighting power to sea and provide marine oil and gas exploration. For example, a cruise vessel spend much of its operational time at an anchor location whereas a large container vessel spend much of its time sailing at its nominal cruising speed. EmmanuelDouglas [EmmanuelDouglas07] reports on a comparison study between a number of different configurations for a typical cruise vessel of 100.000 Gross Register Tonnage (GRT). As for the operational profile, the vessel considered in this report spends about 27% of its time in harbour, 27% of its time in low/medium speed, and 46% of its time in high speed.

In order to accomplish a mission, certain functions are required. Klein-Woud and Stapersma [KleinWoud03] defined the main ship functions and the systems required enabling these function, which is listed in Table 2-1.

Table 2-1 Ship functions

	Function	*System*
Platform	e.g. propulsion and steering	e.g. prime movers and rudders
Operational	e.g. functions of cargo handling for cargo vessels and defensive/ offensive functions for naval vessels	e.g. cranes for cargo vessels and weapon systems for naval vessels
Hotel	Functions that makes life for crew onboard comfortable	e.g. cabins, galley and laundry
General support	These functions may support other functions such as the generation of electricity – electricity is required by hotel loads.	e.g. generation units and hydraulic systems

It must be noted that hotel functions for passengers on cruise vessels are, strictly speaking, part of the operational functions. The operational, hotel and general support systems together are referred to as auxiliary[4] systems [KleinWoud03].

Schulten [Schulten05] defined a *system*, *subsystem* and *components* as follows. A physical *system* usually consists of a number of *subsystems*, which in turn consist of a single or a number of *components*. Using an IFEP vessel as an

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[4] Auxiliary loads in this context include loads other than propulsion, which require elecrtrical power such as light and galley loads.

example, the vessel as a whole could be considered as the system. The power system could be considered as a subsystem whereas the prime movers, transformers, power converters, etc. could be considered as components. However, these classifications depend on the level of system consideration [e.g. Schulten05, Law07 and KleinWoud03]. A diesel engine could be considered as a system itself whereas the turbochargers, fuel injection system, etc. could be considered as subsystems. In this thesis the IFEP power system is considered as the system whereas the prime movers, transformers, etc. are considered as the subsystems. The components include for example transformer windings and circuit breakers.

2.2.2 Classification rules

In this thesis a regular reference will be made to a number of classification rules applicable for the marine shipping industry. These rules are technical standards in relation to design, construction and survey of marine related objects including vessels and offshore platforms. Globally, over 50 organisations provide classification services and guidance for the marine shipping industry. A number of those form the International Association of Classification Societies (IACS), which includes the American Bureau of Shipping (ABS), Lloyds Register (LR) and Det Norske Veritas (DNV) [IACS07]. In this thesis, regular reference will be made to the DNV rules [DNV01].

The International Convention for the Safety of Life at Sea (SOLAS) is considered the most important international convention in relation to the safety of commercial vessels. The first version of this was adopted in 1914 as a response to the tragedy with the RMS Titanic [IMO79]. Presently, SOLAS 1974 is in force with a number of updates and amendments. For example Chapter II-1 of SOLAS 1974 sets requirements for machinery and electrical installations. It covers the safety of the vessel, crew and passengers through ensuring that essential functions are maintained under all circumstances. An amendment; "Revised passenger ship safety standards", came into force on 1 July 2010 [IMO79]. The purpose of this amendment is to improve the survivability of passenger vessels after a damaging incident, which allows the passengers to stay onboard while the vessel sails to port. The implication of this is that increased redundancy and/or inherent reliability/survivability of a vessel's machinery and electrical installation are required [IMO79].

As for naval vessels, more stringent standards are required than for commercial vessels, due to the need for survivability under battle conditions. A number of military standards exist such as the Standardization Agreement (STANAG) and DEF-STAN. STANAG is issued by North Atlantic Treaty Organisation (NATO) where an example is the STANAG 1008 [NATO04], which focuses on electrical power systems onboard vessels. A DEF-STAN example is the DEF-STAN 61-5 Part 4, which focuses on LV power systems for vessels [MOD06].

2.2.3 Mechanically driven marine propulsion and power systems

Conventionally, marine power systems consist of an entirely mechanically driven and coupled system for the vessel's propulsion and a separate electrical power system for the auxiliary systems. A block diagram of a typical propulsion and auxiliary system is presented in Figure 2-1.

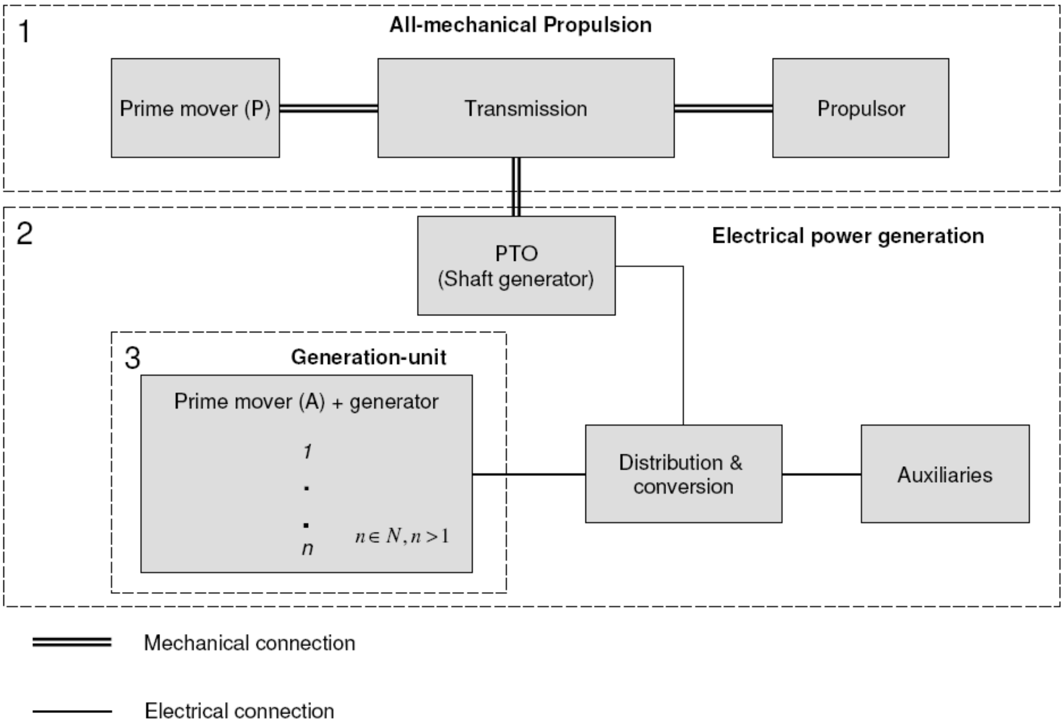

Figure 2-1 Propulsion system

The blocks within box 1 represent the vessel's propulsion system. The prime mover converts chemical energy, usually within fossil fuels, into a rotational mechanical energy output. Depending on the type of vessel and operational profile, diesel engines, steam turbines (ST) or gas turbines can be used as a prime mover or in some cases a combination of these. A mechanical transmission shaft connects the prime mover with the propulsor, where the propulsor converts the rotational mechanical energy from the prime mover into a thrust force [KleinWoud03].

The remaining elements of the system shown in Figure 2-1 (box 2) are used to supply the auxiliary systems with electrical power. The block in box 3 represents a prime mover connected to a generator[5]. The number of generation-units operating in parallel is represented by *n*, which could be for example 4 or 6. The *P* or *A* between the brackets refer respectively to a prime mover used for the vessel's propulsion and a prime mover in a generation-unit. The distribution and conversion block transfers this electrical power to the auxiliary systems in the desired form (e.g. supply voltage (AC or DC) level and frequency). In some cases, an additional Power Take Off (PTO), i.e. a shaft generator, is mounted on the propulsion shaft (either directly or indirectly through a gearbox) to supply the auxiliary system [KleinWoud03].

A number of prime mover/transmission/propulsor system configurations exist, such as combined drives and hybrid drives. A combined drives configuration refers to any combination of mechanical drives (prime movers). For example, diesel engines and gas turbines may be installed on a vessel for a combined or alternative use. In many cases this enhances the overall fuel efficiency through the ability to use the most efficient selection of prime movers at various levels of overall system load. A combination of mechanical and electric drives is referred to as a hybrid drive. A number of reasons exist for using these configurations, which include improved manoeuvring characteristics, improved level of redundancy and the possibility to accommodate a wide range of operating conditions. [KleinWoud03].

The combined drive is usually referred to by an acronym where *CO*, *D*, *G*, *S* and *E* stand for combined drive, diesel engine, gas turbine, steam turbine and electric respectively. In addition *A* and *O* stands for "and" and "or"

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[5] For the remainder of this thesis, a prime mover connected to a generator is referred to as a "generation-unit".

respectively [KleinWoud03]. A number of common configurations are provided in references [KleinWoud03, MTU08, EmmanuelDouglas07 and Lamerton08]. These include *COmbined Gas eLectric And Gas (COGLAG)* and *COmbined Gas Diesel And eLectric (COGDAL)*.

2.3 Technologies for conventional and (future) IFEP/AES vessels

2.3.1 Prime mover

In this thesis the focus will be on gas turbines and diesel engines as these were used in the research work conducted. Therefore other types of prime movers such as steam turbine were not considered.

2.3.1.1 Gas turbines

Gas turbines offer a number of advantages and disadvantages over diesel engines, which include [e.g. McCoy02, Yee08, Ådanes03 and KleinWoud03]:

Advantages:

- Fast starting capability of gas turbines makes them ideal for supplying peak load demands
- Modular construction
- High power to weight ratio (power density) - gas turbines could be placed higher up in the ship's construction
- Low emissions

Disadvantages:

- Requires fuel of high quality
- Low thermodynamic efficiency and high fuel consumption

Regardless of whether a gas turbine is used for aerospace, terrestrial or marine applications, the main components are an intake duct, compressor, combustion chamber, turbine, and exhaust duct [KleinWoud03]. This is illustrated in Figure 2-2, which depicts a Rolls-Royce 36MW MT30 marine gas turbine. This gas turbine is derived from the aerospace Trent 800 engine (successfully used on the Boeing 777 aircraft) [RollsRoyce03]. Gas turbines are often used in naval vessels as the prime mover for the propulsion (e.g. the US Arleigh Burke class destroyer [NavelTechnology08]). However, gas turbines can also be found on commercial vessels such as the RMS Queen Mary II [ShipTechnology08], where the gas turbine is used in a CODLAG configuration. In this case, the gas turbine is used as a generation-unit to supply peak loads.

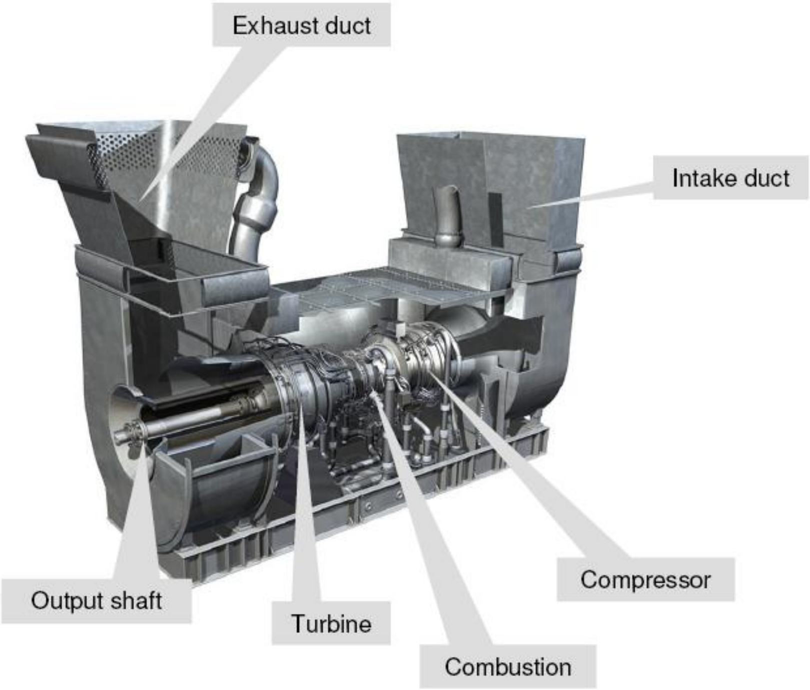

Figure 2-2 MT30 gas turbine [RollsRoyce03]

In a basic single shaft/spool gas turbine configuration, air is compressed by the rotating compressor to a pressure in the order of 10-30 bar. Combustion takes place in the combustion chamber where the compressed air is mixed with injected fuel. The turbine then allows the hot gasses to expand to atmospheric pressure. The energy from the turbine is used to rotate the compressor and to deliver power to the load. This process can be described by an ideal Brayton cycle [KleinWoud03].

A number of technologies can be used to improve the thermodynamic efficiency of a gas turbine. This is sometimes referred to as advanced cycles. For example recuperation is a technology whereby the compressed air is preheated by the turbine exhaust gasses through a heat exchanger. Another technique is called inter-cooling whereby the air between the compression stages is cooled.

A single shaft/spool simple cycle gas turbine is illustrated in Figure 2-3a where *C* and *T* are referred to as compressor and turbine respectively. This type of gas turbine is used in generation-unit applications where the speed is maintained constant. The load on the gas turbine is not allowed to become too large as this will force the speed to go down [KleinWoud03].

For applications where the load changes (such as a direct mechanical drive of a propeller [KleinWoud03] and in generation-units [RollsRoyce03]), a separate Power Turbine (PT) is used. This type of gas turbine is referred to as a two shaft/spool gas turbine. A two shaft/spool simple cycle gas turbine is illustrated in Figure 2-3b where *PT* refers to power turbine. This type is mostly used for marine applications since it has a wider operating envelope [KleinWoud03].

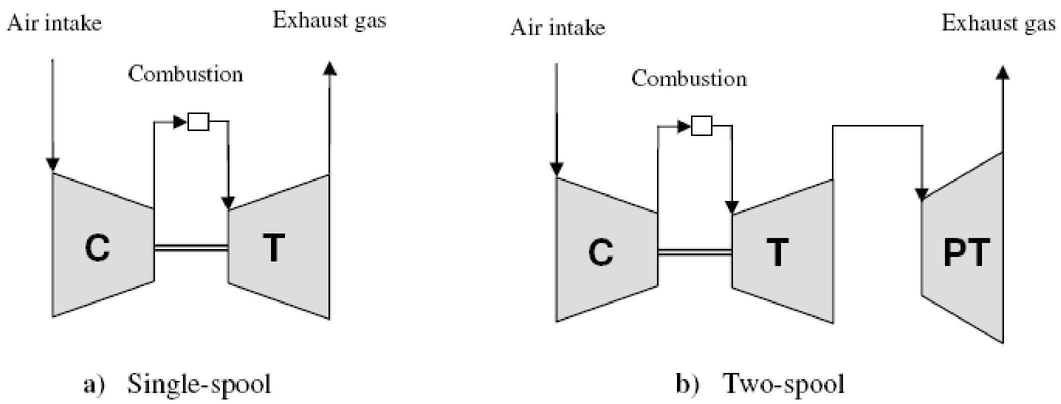

Figure 2-3 Single-spool and two-spool gas turbine

For driving a propeller, a gear box is required as the output speed of the gas turbine is typically between 3000 and 7000 rpm [KleinWoud03]. Typical data of marine gas turbines in an IFEP system are presented in Table 2-2. In general gas turbine transients ranges are: thermal transient (0-1Hz), shaft transients (1-5Hz) and gas dynamics transients (5-50Hz) [CunhaAlves03].

Table 2-2 Typical data gas turbine

	MT30 *[RollsRoyce03]*	*WR21* *[RollsRoyce00]*	*LM2500+* *[GeneralElectric06]*
Nominal power (MW)	36	25.2	30.2
Specific fuel consumption (kg/KWhr)	0.21	0.2 -0.35	not specified
Nominal speed PT (rpm)	3600	3600	3600
Thermal efficiency (%)	>40	not specified	39
Example vessel	*HMS Queen Elizabeth* (Royal Navy's Future aircraft carrier)	*HMS Daring* (Type 45 Destroyer)	*RMS Queen Mary II* (Cruise liner)

2.3.1.2 Diesel engines

Diesel engines are commonly used for the propulsion of ships where either 2-stroke or 4-stroke diesel engines are employed. Due to its high power and slow-speed characteristics, 2-stroke low speed diesel engines are usually directly connected to the propeller without an intermediate gearbox. Typical applications include large cargo vessels such as container vessels and bulk carriers. 4-stroke high-speed and medium-speed diesel engines are usually connected to the propeller through a gear box due to their low-power - high-speed characteristics. Typical applications are smaller cargo vessels. In addition, 4-stroke diesel engines are used in generation-units [Ådanes03]. Table 2-3 shows examples of diesel engines used on both more conventional powers systems and on an IFEP vessel.

Table 2-3 Typical data diesel engines

	WärtsiläFlex96C ***[Wärtsilä08a]***	***Wärtsilä64*** ***[Wärtsilä08b]***	***Wärtsilä Genset 20*** ***[Wärtsilä08c]***
Type	2-stroke	4-stroke	4-stroke
Purpose	Propulsion	Propulsion	Generation-unit
Number of cylinders	14	6	4
Nominal power (MW)	84.42	12.9	1.665
Specific fuel consumption (kg/KWhr)	0.17	0.164	0.185-0.194
Nominal speed (rpm)	102	327.3-333.3	900
Example vessel	*Emma Maersk* (Container vessel [Maesrk08])	*Schippersgracht* (Multi-purpose cargo vessel [Spliethoff08])	*Bourbon Orca* (DP2 Anchor Handling Tug Supply Ship (AHTS) [Bourbon08])
	Conventional	Conventional	IFEP

Typical efficiencies reported in [EmmanuelDouglas07] are in the range of 50% for 4-stroke and 52% for 2-stroke diesel engines.

2.3.2 Electrical system

2.3.2.1 Electric distribution system

This (sub)system has a number of objectives and associated components to achieve these objectives. The main objective is to transfer the electrical power from the generator-units to the auxiliary loads. It must ensure that the power delivered is at the right format (e.g. voltage level) and satisfies the appropriate standards (e.g. LR). In addition, measures need to be taken to protect the system and people on board the vessel from the potential effects of electrical faults, such as short circuits and sustained overloads.

A number of components are employed to achieve these objectives. This includes switchboards, cables, transformers and circuit breakers. A typical distribution system, for example found on many passenger and naval vessels, is illustrated in Figure 2-4. Both main switchboards (MV voltage level) can supply their counterpart through the interconnection cable in the case of a generation-unit failure on either main switchboard. Apart from one or more main switchboards, every vessel has an emergency switchboard, which is supplied by an emergency generation-unit. In the harbour, there is a possibility to supply the main switchboard through a shore connection. Auxiliary systems near the main switchboards are connected directly to these boards whereas for system farther away, distribution panels are used. Transformers are used to supply secondary panels (LV voltage level) if some auxiliary loads require a different supply voltage than the main switchboard's voltage [e.g. KleinWoud03 and Ådanes03].

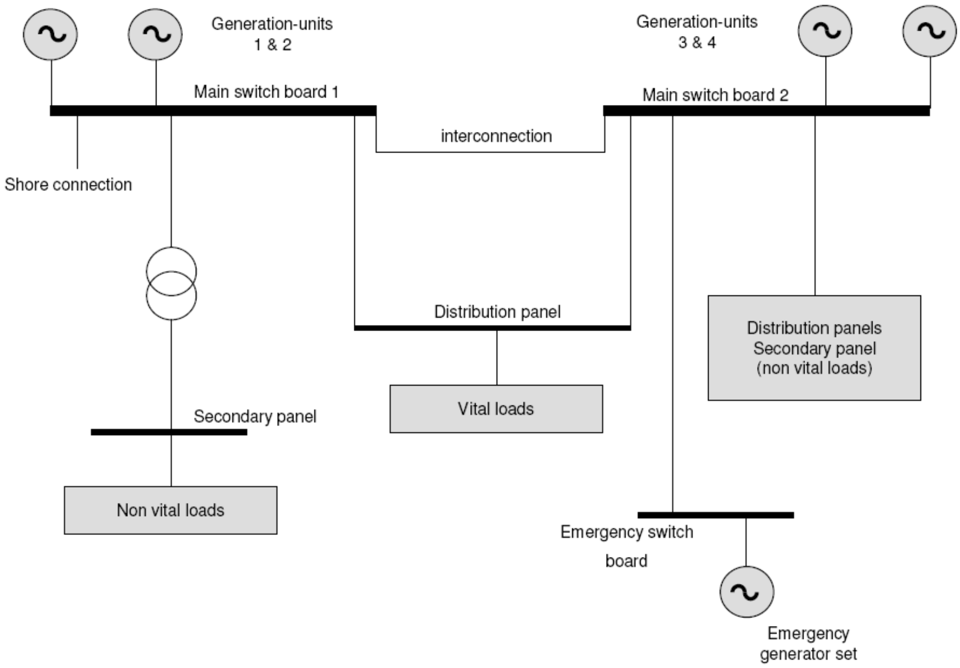

Figure 2-4 A typical marine distribution network

With IFEP, there is generally a direct connection from the main switchboard to the propulsion motors. A form of power conversion, using power converters, is normally required to control the speed and rotational direction of the motor. MV voltage levels may vary per vessel and depends on parameters such as vessel type, installed generator capacity (installed power) and power rating of the electrical motors. Typical voltage levels include 13.8kV, 11kV, 6.6kV, 4.160kV, 690V, 440V, 230V and 120V. The higher voltage levels are required if the installed power causes too high nominal and short circuit currents. Increasing the voltage levels reduces the current levels [Ådanes03].

2.3.2.2 Electric machines

Electric machines convert mechanical rotational energy to electrical energy in case of a generator or vice versa in case of a motor. These machines have a significant impact on the system as the power ratings can be large with respect to the total installed power. For example, onboard the RMS Queen Mary II, the 4 electric propulsion motors of 21.5 MW each [Ingenia06] are large with respect to the total installed power of approximately 120MW. Similarly, the power rating for the electric generators is large. In addition to main propulsion duties, electric machines are also used as motors to drive pumps, winches and bow thrusters.

2.3.3 Propulsor

Although the design of a vessel's hull and propeller is of concern to a naval architect, a high level discussion is required as the marine engineer requires data on the vessel resistance and propeller characteristics in order to specify the propulsion power. A number of propulsor types exist, such as Voith-Schneider and water jets, though the most commonly used propulsor is the screw propeller [KleinWoud03, Ådanes03]. Therefore, only the screw propeller[6] will be considered in this thesis.

Two propeller types exist, which are the Fixed Pitch Propeller (FPP) and the Controllable Pitch Propeller (CPP) [KleinWoud03, Ådanes03]. As the pitch of a FPP is fixed, the speed has to change in order to control the thrust. Therefore the (sub)system driving the propeller (e.g. electric propulsion motor or diesel engine) must be able to change their speed. With the CPP the pitch of the propeller can be altered in order to change the thrust at constant speed. Combinations of variable speed with CPP can be selected for some applications in order to achieve higher efficiency and faster response. However, CPPs do have its disadvantages over FPPs, which include increased complexity, costs and susceptibility for propeller cavitation.

2.4 Integrated Full Electric Propulsion

2.4.1 Introduction

IFEP has become of interest within the marine shipping industry for over two decades. This technology has changed the way marine power systems are designed and operated. As opposed to more conventional marine power systems, IFEP utilises a common set of *n* generation-units, which provide the power for both the vessel's propulsion and auxiliary loads. This is illustrated in Figure 2-5, which represents a typical IFEP system. Note that in this case an electric motor drives the propeller instead of a prime mover.

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[6] For the remainder of this thesis, the screw propeller is simply referred to as "propeller"

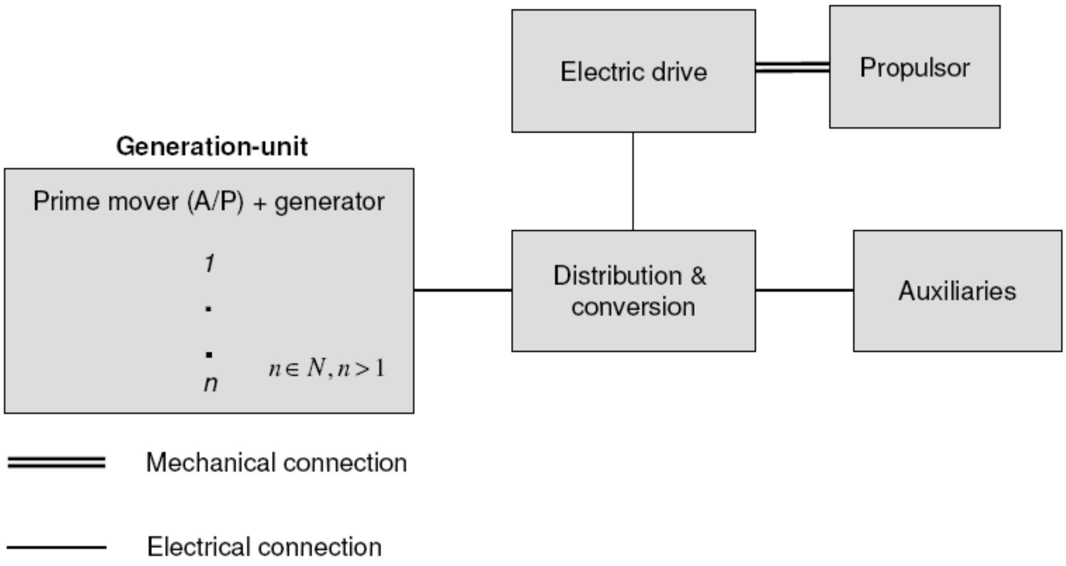

Figure 2-5 Block diagram IFEP

2.4.2 Advantages and disadvantages of IFEP systems

Potential advantages and disadvantages of IFEP in comparison with conventional marine power systems are discussed in a number of publications including [Hansen01, Ådanes03 and Hodge95, Kanellos12].

2.4.2.1 General advantages of IFEP

Improved fuel economics

The power required for propulsion is not constant and may change significantly depending on the type of vessel and operation mode. For example, cruise vessels and Field Support Vessels (FSV) often operate well below maximum speed such as in DP mode. Typically, DP vessels operate half of its time in transit and half of its time in DP [Ådanes03]. Using the more conventional propulsion system during these operating conditions would reduce the efficiency of the prime movers as these would not operate at their optimum operating point for most of the time. If the load on the diesel engine is less than 50 % of its Maximum Continuous Rating (MCR), the efficiency will drop fast. As a consequence, the combustion will become less efficient releasing higher levels of NO_x ad SO_x [Ådanes03]. IFEP is particularly suited for vessels with such operating profiles and possess in addition a relatively large base load (e.g. auxiliary load). A large base load would maintain the loading on the prime mover (or on a subset of the overall set of prime movers) at a high enough level to operate near optimum efficiency levels for most of the time [Hodge95]. Potentially FSVs can save approximately 700 ton fuel per year [Ådanes03].

Improved manoeuvrability

Reversing the rotating direction of the propeller with more conventional power systems is not straight forward. As diesel engines and gas turbines will not easily reverse rotational direction, other complex technologies have been used such as revering gearboxes and CPP. However, with the technological developments of electric machines and solid-state power converters[7], reversing the direction of the propeller is relatively straightforward. Therefore IFEP employs electric motors to drive the propeller. Apart from placing the electric motor inside the vessel, an electric motor can also be built in a pod, which is attached underneath the hull and near the stern of the vessel. These pods can either be fixed or rotating. In the latter case the pods are designed to rotate in the horizontal plane, which are referred to as azimuthing pods (e.g. azipods® [ABB], and Mermaid® [RollsRoyce14]). Rudders are therefore no longer required. Pods improve manoeuvrability, which is particularly useful during harbour and DP operation. This technology is often employed on commercial vessels such as cruise vessels, cruise liners and FSVs and was first introduced in the early

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[7] Hereafter simply termed "power converter"

1990’s [Ådanes03]. An example application in a cruise liner is the RMS Queen Mary II [Ingenia06], which uses 4 pods, 2 fixed and 2 rotating.

Flexibility in machinery allocation

As opposed to conventional propulsion systems, the prime movers are no longer constrained in terms of position by being required to couple directly with the propeller. This means that, theoretically, the generation-units can be placed anywhere in the vessel. This is useful from a naval architecture point of view as this may help to improve the vessel’s stability. A more optimum machinery allocation may also free up valuable space, which could be used for additional cargo or passenger cabins. For naval applications, having a distributed propulsion system can also act to improve overall vessel survivability.

Improved power availability

Failure of one generation-unit does not necessarily endanger the power supply to the electric propulsion motors, if multiple generation-units are operating in parallel. Power can therefore be supplied by the remaining generation-units. This is not easy achievable with more conventional power systems whereby the propeller is mechanically connected to a prime mover (no or limited redundancy).

Simplified maintenance

As the prime movers operate at a more optimal operating point for most of the time, less maintenance is required. Instead of having a large prime mover for the propulsion and n number of smaller prime movers for the auxiliary loads, one type of n prime movers can be used with IFEP. This eliminates the need for having spare parts for different types and enables more maintenance activities to be carried out during in-service mode of the vessel due to the inherent redundancy available in the system.

Reduced noise and vibrations

Due to a smaller or absence of a mechanical shaft, propeller noise and vibrations are reduced.

2.4.2.2 Advantages for typical IFEP vessels

Special vessels

IFEP also offers potential benefits for special vessels such as icebreakers, Offshore Supply Vessels (OSV), LNG tankers and ferries [Ådanes03, Sekula03 and Benatmane07]. Newell *et al.* [Newell99] reported that a single diesel-electric LNG carrier has a daily fuel saving of 40 tonnes, a daily reduction in CO_2 emissions of greater than 140 tonnes per day and a reduction in SO_x emissions of 7 tonnes per day, when compared with a conventional steam turbine, directly mechanically-propelled vessel.

Commercial vessels

For over a decade, IFEP has been the main choice of propulsion configuration for the cruise shipping industry. One of the main reasons why cruise vessels benefit in particular from IFEP is the relatively large auxiliary load in combination with their operating profile. The large propulsion and hotel loads on a cruise liner during cruising could be in the order of 86 MW and 16 MW (The RMS Queen Mary II) respectively [Ingenia06]. In comparison with a container vessel of similar propulsion power this is significant. Apart from cruising, there are other operational profiles for cruise vessels such as harbour and anchorage. Often these operational modes require the use of complex DP systems. Table 2-4 presents characteristics of some existing commercial vessels employing IFEP technology.

Table 2-4 Commercial IFEP vessels

	RMS Queen Mary II *[Ingenia06,Thome06]*	*British Emerald* *[Benatmane07]*
Type	Cruise liner	LNG carrier
Year built	2003	2007
Total installed power (MW)	117,2	38.5
Propulsion power (MW)	86	29.7
Voltage level MV (V)	11000 AC	6600 AC
Voltage level LV (V)	not specified[8]	450 AC

Naval vessels

IFEP also offers several advantages for the military shipping industry. However, since the design and operational requirements are more stringent than it is the case for the commercial shipping industry (e.g. survivability requirements and concerns over reliability of IFEP systems and components), the implementation of IFEP has been at a slower rate. The increased interest in IFEP for naval vessels has arisen as a result of enabling technologies reaching maturity, such as power converters, more efficient and reliable electric machines and computer technology [Little03, Hodge95]. Among the first electric battle vessels equipped with IFEP technology is the Type 45 Daring class Destroyer for the Royal Navy [BAESystems08]. Examples of naval vessels fitted with IFEP are presented in Table 2-5.

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[8] Exact and consistent data was not found in the public domain

Table 2-5 Naval IFEP vessels

	HMS Daring class [Norton06]	*HMS Queen Elizabeth class [Webster07]*
Type	Type 45 Destroyer	Royal Navy's Aircraft Carrier (CVF)
Year built	2006	2014-2016
Total installed power (MW)	44	110
Propulsion power (MW)	40	not specified
Voltage level MV (V)	4160 AC	11000 AC
Voltage level LV (V)	440 AC	not specified

2.4.2.3 Disadvantages of IFEP

Higher investment costs

The capital investment costs of IFEP systems are higher in comparison with more conventional power systems [Pereira08]. A paper presented by Völker [Völker13] shows that the investment costs of an IFEP system compared to conventional power systems are high indeed; 2-3M€ more for a harbour tug boat. Even with fuel-savings over the lifetime of the ship, return in investment costs may be difficult. However, the paper does not take into account the additional cost savings by for example increased manoeuvrability (less or no tugs required during harbour operation).

Additional losses

As more components (transformers, power converters, etc.) are placed between the prime movers and propeller, the losses will be increased at full load [Ådanes03]. However, it must be noted that the efficiency with electric transmission remains higher during part load operation [Hodge95].

2.4.3 All Electric Ship

IFEP can be considered as a fundamental step towards the realisation of the All Electric Ship (AES), as it provides a testing ground for conceptual future technologies [Norman06b]. AES moves the IFEP concept a step further through the electrification of auxiliary systems that were previously powered by hydraulics or perhaps via mechanical drives of some sort. However, the path towards the AES remains long and many technological challenges remain to be addressed. Table 2-6 [Schuddebeurs06] describes some of the definitions that can be found throughout the literature. Part of this table is based on the work conducted by Little *et al*. [Little03]. At the moment the technology is somewhere between the IEP and the IFEP. The focus of this thesis will therefore be mainly on IFEP technology.

Table 2-6 Definitions and classifications of electric ship

Classification	*Definition*
Diesel-Electric	Separate diesel-generation plant for propulsion and auxiliary loads
Hybrid propulsion	Combination of a mechanical drive and an electrical drive for vessel propulsion
IEP (Integrated Electric Propulsion) **DEP (Diesel Electric Propulsion)**	Common power source for both the vessel's propulsion and vessel services
IFEP (Integrated Full Electric Propulsion), UK **IPS (Integrated Power Systems), US**	Takes IEP a step further, in terms of inclusion of advanced power converters and energy storage
ES[9] (Electric Ship) **AES (All Electric Ship)** **MES (More Electric Ship)**	Combination of IFEP advanced prime movers and electrification of auxiliary systems such as hydraulics and pneumatics.
Electric Warship	System where high powered weapons and sensors take advantage of the high available level of system power

2.5 Key technologies and research challenges for IFEP vessels

If IFEP (and eventually AES) technologies are to be widely adopted successfully, a number of key research challenges must be addressed. The need for addressing IFEP research challenges has been widely recognised internationally by vessel designers, vessel owners, navies and research institutes.

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[9] For the remainer of this thesis ES refers to Energy Storage

For this thesis, a number of these key research challenges have been categorised in three research themes, each consisting of a number of IFEP key techniques and/or technologies. These include: *Analysis techniques*, *Core technologies* and *Advanced technologies* where *Analysis techniques* refers to techniques that can be used during the design and in-service phases including modelling and simulation. *Core technologies* refers to technologies, such as power system protection, that must be employed in order to operate both conventional and IFEP power systems in a secure and satisfactory way. On the other hand *Advanced technologies* refers to desirable technologies that have not yet been widely adopted but may offer additional benefits such as increased fighting capabilities for naval vessels and increased power to weight ratios. It must be noted that *Advanced technologies* may also require more advanced *Core technologies* and *Analysis technologies*. Figure 2-6 illustrates how modelling and simulation tools (suitable for multi-domain systems) relate to both *Core technologies* and *Advanced technologies*. The former in combination with the IFEP power system can be analysed and designed with modelling and simulation tools. The latter may be included in future vessels where modelling and simulation can help to assess the effect of these technologies on the IFEP power system and vice versa. In addition, two more groups, *Constraints* and *Outcomes*, have been added to the diagram.

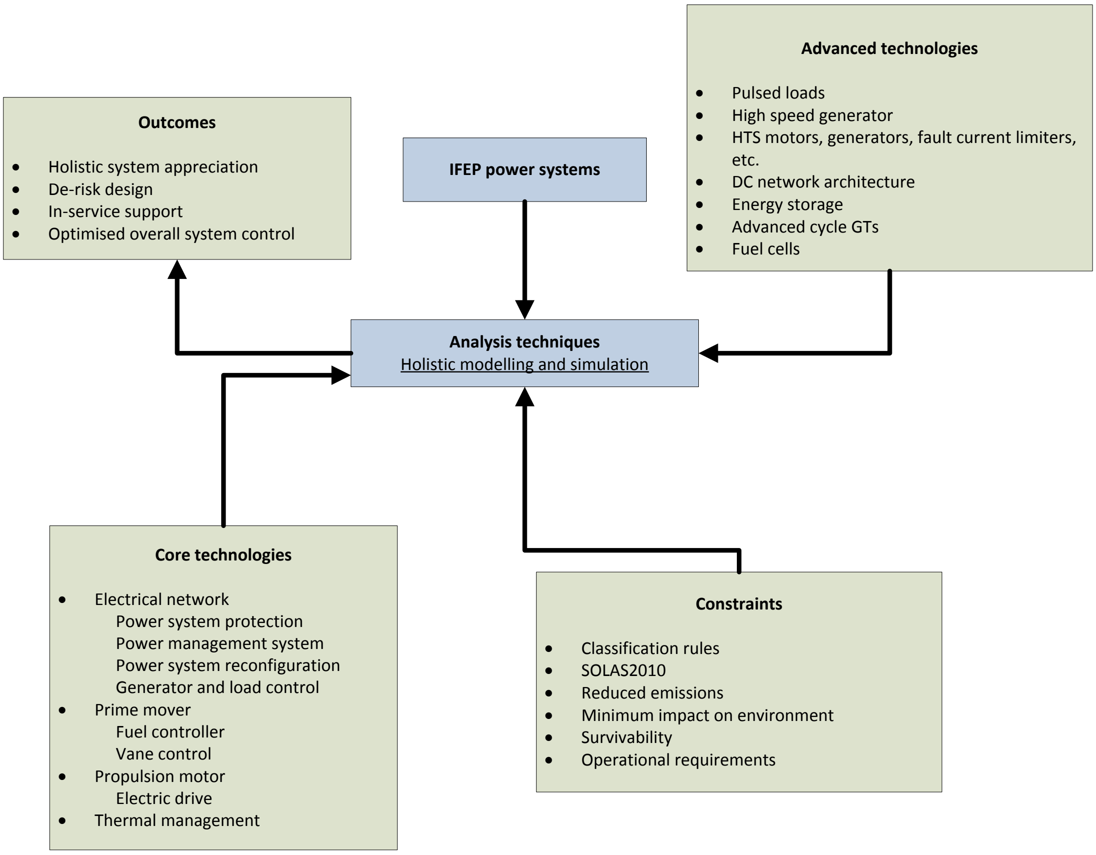


Figure 2-6 Holistic modelling and simulation approach

Constraints relates for example to classification rules and operational requirements. The ability of a vessel to conduct a crash stop within a certain distance could be an operational requirement. The *Outcomes* represents the only output of the Holistic modelling and simulation group. The *Outcomes* can for example be used as an in-service support tool during the operational life of the vessel.

2.5.1 Analysis techniques

Compared to terrestrial power systems, the power system onboard IFEP vessels is small in terms of overall scale and capacity. However, the total installed power is large relative to the physical size of the system, which makes IFEP a (in some cases extremely) power-dense system. In addition, the line impedances and system inertia are relatively small [Hansen01]. Consequently, perturbations, including those caused by short circuits and large load changes, can easily propagate through and impact upon the rest of the system causing system-wide effects, which may include severe voltage, power and frequency transients [Nagaraj07]. As a result, it is important to better understand and characterise the response of these integrated systems of future IFEP systems. Given the complexity of this problem there is a requirement for improved modelling and simulation, which for example provides capabilities to capture the interactions adequately between different physical domains [e.g. Norman06b, Schuddebeurs07b, Schuddebeurs10 and Thirunavukarasu13]

It has been widely recognised that modelling and simulation of marine power systems has the potential to reduce the costs and risks during the design, test and acquisition stages significantly [Deverill03, Monterrain03, Ferreira04, Norton07]. In addition, modelling and simulation can be used as in-service support, which allows for example system upgrade assessments or fault diagnosis [Bennett07, Norton07]. However, due to the complexity of the system and the associated computational burden, different modelling approaches have been adopted. One such an approach is using simplified models [Castellan07]. Other techniques include simple state-space representation of the network [Abdeljalil05]. The next chapters will provide a more detailed literature review on high-fidelity modelling and simulation of complex systems such as IFEP.

2.5.2 Core technologies

2.5.2.1 Power system protection

Power system protection for marine power systems, as compared to other engineering disciplines, has not changed significantly over time. Generally these protection systems have been fit for purpose. However, the introduction of the IFEP concept has challenged the present power system protection practise on board vessels. Reasons for this include an increased fault current due to the growth in installed generation capacity. In addition the proliferation of advanced power converters and the concept of novel loads require a paradigm shift in power system protection for marine systems. Current measurement is used in more conventional power system protection for determining whether a fault exists. However, with power converters in the fault current supply path, it is likely that prospective fault currents are subjected to instantaneous reduction by protective elements in the power converters. As a consequence, the fault currents may not be significantly greater than the full load current. Therefore, over-current protection will have difficulties to detect a fault [Booth08].

2.5.2.2 Power system reconfiguration

With IFEP systems, an increasing number of operational-critical (vital) systems will depend on the availability and quality of electrical power. For example, for an OSV operating in DP mode, the vessel must remain in position and keep its heading even under severe environmental conditions (e.g. waves and current). For a naval vessel, the availability of combat systems (e.g. weapon and radar) and the availability of propulsion power are vital under many operating conditions. For example, physical damage caused by a missile strike, may result in part of the power system to fail. However, it is critical that the non-affected systems remain supplied with power in order to increase the chances of survival. Therefore a fast and reliable automatic reconfiguration function for the power system is required – this may also include reconfiguration and/or adaptation of the generator and overall power system control and protection systems.

Nagaraj *et al*. [Nagaraj07] have presented a literature review on marine power system reconfiguration. It is stated that power system configuration is almost always formulated in terms of an optimisation problem where the reconfiguration algorithm seeks for the switch configuration that maximises or minimises a given system characteristic. For terrestrial power systems, objectives for reconfiguration include: resistive loss reduction, enhancement of voltage profile and service restoration. As for large systems, the search space can be extensive, heuristic rules can be used to reduce the search space. These heuristic rules are based on experience and system knowledge. A large research project in the US, managed by the Office of Naval Research (ONR), is the Electric Ship Research and Development Consortium (ESDRC), which involves a dozen universities in the US [Carpentier05, Chalfant11]. One of the main research projects within the ESRDC is associated with the future development of the US DGG 1000 destroyer [NorthropGrumman07]. A main area of research is the use of Multi Agent Systems (MAS) for power system reconfiguration [Wang05].

2.5.2.3 Power management system

In complex systems such as IFEP, there are numerous subsystems/components, which require some form of control [Radan08]. Examples include speed control for the propulsion motors, DP control and HVAC control. As the electrical distribution system connects all these subsystems/components, transients caused by one subsystem/component may propagate to the rest of the subsystems/components [Ådanes03]. Therefore, an optimised integrated control strategy is required, which will consider the control aspect of the overall system from a holistic point of view. This will then ensure an improved overall system performance.

2.5.2.4 Thermal management

Due to the increase in electrical components and their power ratings, including electric machines and power converters, a well suited thermal management system is required to get rid of the generated heat [Faruque09, Fang09].

2.5.3 Advanced technologies

As a result of the increased interest in IFEP, a number of novel technologies have been proposed to be implemented on board IFEP vessels. Some of these technologies will increase the operational capabilities of vessels whereas others will potentially improve the efficiency of the power system. A number of these novel technologies will be discussed briefly.

2.5.3.1 Energy storage

Challenges with Energy Storage (ES) include the potential and significant contribution to fault currents, sizing, and placement of devices. ES has been considered for a number of functions on board vessels. Firstly, novel pulsed loads such as the Electromagnetic Rail guns (EM) and the Electromagnetic Aircraft Launch System (EMALS) require a short-term, but extremely high-power (sometimes referred to as pulsed power) supply of energy for their operation. ES can act as a buffer between the load and power system, thereby minimising the requirement for high-capacity generation and distribution networks [Luo12]. Secondly, in case one of the prime movers fails and/or in the event of a failure/fault on an element of the distribution system, ES could support the power system (in terms of supplying critical loads) for some time. This application of energy storage may be termed as supporting the "ride-through" capability of the vessel's power system [Hoffman10]. Finally, ES can be used for load levelling. For example, significant cyclic load variations may result in an unacceptably varying system frequency as the generator controls fluctuate in response to the constantly changing power balance. ES interacts with the loads in order to minimise the variation as seen by the power system [Elders08] through "peaking and troughing" the demand profile by supplying and absorbing power as necessary. Similar ideas have been investigated for future decentralised terrestrial power systems where excessive frequency variations are expected due to the employment of renewable energy sources (RES) and the reduced system inertia [Visscher08]. In Europe, research has been conducted into the development of the UK Type 45 Destroyer. A number of papers have been published on the Electric Ship Technology Demonstrator (ESTD); e.g. Mattick *et al*. in [Mattick05]. The main objectives of the ESTD have been to de-risk the Type 45 Destroyer through development and demonstration prior to implementation. Research areas include the widespread use of power converters and the potential applicability of ES.

2.5.3.2 Pulsed loads

EM is a serious contender for future naval vessels [Hoffman10]. Muzzle velocities in excess of 2 km/s and with a kinetic energy around 60MJ can be obtained. Therefore a projectile fired from the EM will be very destructive. Advantages of EM over conventional ammunition includes, increased firing range, no need for propellant, increase in projectile storage density and reduced cost per round [McFarland03]. Other pulsed loads include the EMALS, which uses a Linear Induction Motor (LIM) to launch an aircraft on an aircraft carrier. In order to provide the high-energy pulses to these loads, ES devices such as flywheels can be used.

2.5.3.3 DC distribution

Since the development of electricity, AC has been preferred over DC transmission and distribution systems [Starke08]. Similarly, since the introduction of IFEP technology, there have been regular discussions within the marine shipping industry and academia whether to use AC or DC as the preferred distribution system on board vessels. Advantages of AC over DC include an easy conversion of voltage levels using power transformers. However, with the technological improvements in power converters and electric machines, DC has now been used for a number of applications including the International Space Station (ISS) and High-Voltage DC (HVDC) terrestrial transmission [Zgliczynski06]. Advantages of DC over AC include transmission of 23.5% more power using the same mass of copper [e.g. Hodge07 and Starke08] and no AC noise coupling [Zgliczynski06]. Partly because of these “general DC advantages”, DC has now become the focus of interest within the marine shipping industry [Nebb12]. In addition it is expected that future loads and ES devices, such as EMALS [Zgliczynski06] and fuel cells respectively [Starke08] require DC distribution. However, one of the main disadvantages includes the difficulties in breaking the DC currents and the potential increased fault current contribution due to the capacitive filtering.

2.6 Chapter summary

In this chapter an introduction to the IFEP and the AES concepts was presented. As opposed to more conventional power system, IFEP utilises a common power source to supply both the vessel’s propulsion and auxiliary loads. IFEP has gained interest of both the commercial and military shipping industry over the last few decades since IFEP offers several advantages, which include operational flexibility and increased overall system efficiency. However, as IFEP is fundamentally different from more conventional marine power systems, present engineering practice may no longer be adequate. A number of key challenges were reviewed in this chapter including the implementation of energy storage and the need for more advanced modelling and simulation techniques.

Chapter 3 Multi-domain Modelling and Simulation

3.1 Chapter overview

In this chapter key challenges of integrating several high-fidelity models from different subsystems and domains, such as IFEP systems, into a single unified model will be discussed. The scope of this chapter is limited to the mechanical and electrical domain but has also application across other domains. The work presented in this chapter has been published in a number of papers including [Schuddebeurs07b, Schuddebeurs08a, Schuddebeurs08b and Schuddebeurs10].

3.2 Introduction

Over the years systems have become larger and more complex, often containing several subsystems and components from more than one physical domain. Typical multi-domain (sometimes referred to as multi-physics [Breedveld04] or multi-disciplinary [Schulten05]) systems, such as power plants or airplanes [Khan14], include subsystems from the mechanical (e.g. gear boxes), thermal (e.g. gas turbines and steam turbines) and electrical (e.g. electric machines and power converters) domain. Multi-domain systems with all its subsystems must operate satisfactorily thereby meeting the applicable classification rules and operational specifications. Therefore understanding, both during the design and in-service, the complex interactions between the several subsystems and domains is required. However, full-scale hardware testing of an entire complex and large multi-domain system is often not an option due to cost and time limitations [Samarskii02]. Instead modelling these systems mathematically and solving these (often differential) equations by computers (i.e. modelling and simulation), offers a relatively fast and cost-effective solution to assess the impact of design decisions on system behaviour [Sinha01]. Nevertheless, in this case it is desirable to have a single unified model, which contains all the subsystem models. This allows a far better understanding of the interactions taking place between the individual subsystems and domains than would otherwise be possible considering the subsystems and domains in isolation. However, integrating models from different domains into a single unified model is not a trivial exercise.

3.3 Generic aspects of modelling and simulation

The following modelling and simulation definitions are considered to be most relevant for the remaining of this chapter and thesis.

3.3.1 The concept of a model and simulation

Knepell and Arangno [Knepell93] defined a conceptual model as follows: *"verbal description, equations, functional relationships, or natural laws that attempt to define the problem entity (problem entity: an entity, situation, or system selected for analysis)"*. The same authors defined simulation as: *"modelling of systems and their operations using various means of representation"* In a DEF STAN publication called: Definitions of Modelling Standards – Marine Electrical Power Systems [MOD07], modelling and simulation is defined as follows: *"A model is a representation of a system, either in theoretical terms, or as an executable in some suitable software environment"* whereas a simulation is defines as *"a model that is executable in some suitable software environment"*. Although this standard is applicable to marine power systems, it can equally be used for other applications.

3.3.2 Simulation speed

The speed of a simulation is defined in [MOD07] as *"the ratio of simulation time to real time*". Hereafter, the speed of the simulation is termed "(simulation) execution time". Different levels of simulation execution time can be defined as shown in Table 3-1.

Table 3-1 Levels of execution time

Level	*Description*
Predictive	Faster than real time
Hard Real Time	Strictly real time – for example suitable for HIL
Real Time	Approximately real time
Retrospective	Up to 100 times slower than real time
Slow	More than 100 times slower than real time

3.3.3 Model fidelity

In [MOD07] fidelity is defined as: *"a measure of the granularity of detail present in the real world, which should be represented within a model or simulation"*. In this standard five levels of fidelity have been identified ranging from *very low* up to *very high*. Each level is associated with certain frequency phenomena they can capture. For example fidelity level *very high* can observe radio frequency up to a maximum of approximately 10MHz. However, as mentioned by Norton *et al.* [Norton07] there is a trade-off between model fidelity and simulation execution time. High-fidelity models allow one to observe high frequency phenomena but at the same time the simulation execution time may be unacceptably long.

3.4 Modelling and simulation of IFEP systems

Modelling and simulation of complex multi-domain systems will be the main focus for the remainder of this thesis. In particular the development of the AMEPS model will be discussed in detail.

3.4.1 AMEPS model

At the beginning of 2005, the EPSRC funded the collaborative research project AMEPS. It was initiated by pooling the expertise of three UK Universities including Strathclyde, Manchester and Cranfield [Norman06b]. The objective of the AMEPS project was to develop an efficient modelling and simulation capability, which could be used to investigate the holistic behaviour of IFEP systems under normal and extreme operating conditions. This modelling and simulation capability was achieved by developing an integrated-model, which combines models from different subsystems /domains present in IFEP at an adequate level of fidelity. This AMEPS model is based loosely on the Type 45 Daring Class Destroyer; the most recent class of vessels ordered by the British Royal Navy. Table 3-2 indicates to what part of the AMEPS model each partner university contributed.

Table 3-2 AMEPS partner contributions

University	*Contribution*
Cranfield	Developing a gas turbine model with advanced cycles.
Manchester	Developing an advanced propulsion motor model including power converter. In addition a propeller and vessel model had to be provided.
Strathclyde	Developing the electrical distribution system. In addition the propulsion motor and gas turbine models had to be integrated with the electrical distribution system in a computational efficient way.

The AMEPS model was built using a combination of different simulation software tools including FORTRAN and Matlab® /Simulink®/SPS. Each of the submodels developed was built using the software tool considered most appropriate by the AMEPS team for the underlying technology, which is outlined below [Schuddebeurs07b].

FORTRAN: Cranfield University has extensive knowledge in gas turbine technology and experience in modelling and simulation of this in the programming language FORTRAN. Therefore this tool was selected to model the gas turbine in the AMEPS model.

Matlab® /Simulink®: This tool allows for an equation based modelling approach, which becomes handy when subsystem/component models have to be built from first principles. This versatile tool was therefore selected by the University of Manchester to model and simulate the propulsion motor, power converter, propeller and vessel. In addition this tool is also powerful in case control systems have to be modelled and simulated. This tool was therefore selected by the University of Strathclyde to model the system-wide control system.

SimPowerSystems™: This toolbox, which is part of the Simulink® environment, is very powerful in the sense that it allows a modeller to build an electrical network using submodels of electrical components rather than to build an equation-based equivalent. These electrical components are contained in a library, which includes transformers, cables and power converters. This tool was therefore selected by the University of Strathclyde to model and simulate the electrical distribution system.

A single line diagram of the AMEPS model is presented in Figure 3-1 where PM represents the propulsion motor. The network architecture of the Type 45 Daring Class Destroyer is of the radial type, which consists of two similar sections connected by tie- breakers. These sections can either operate as two independent sections (less prone to system-wide disturbances, which may propagate across the entire system) or as one system, which increases the redundancy. The AMEPS model is loosely based on a single section (either the port or starboard side) of the Type 45 network as operating the system with two independent sections is not uncommon. Considering a single section also reduces the complexity of the model without compromising the required model fidelity. Furthermore the 2 diesel engine of 2MW each was not modelled yet as the focus was initially on the large gas turbines.

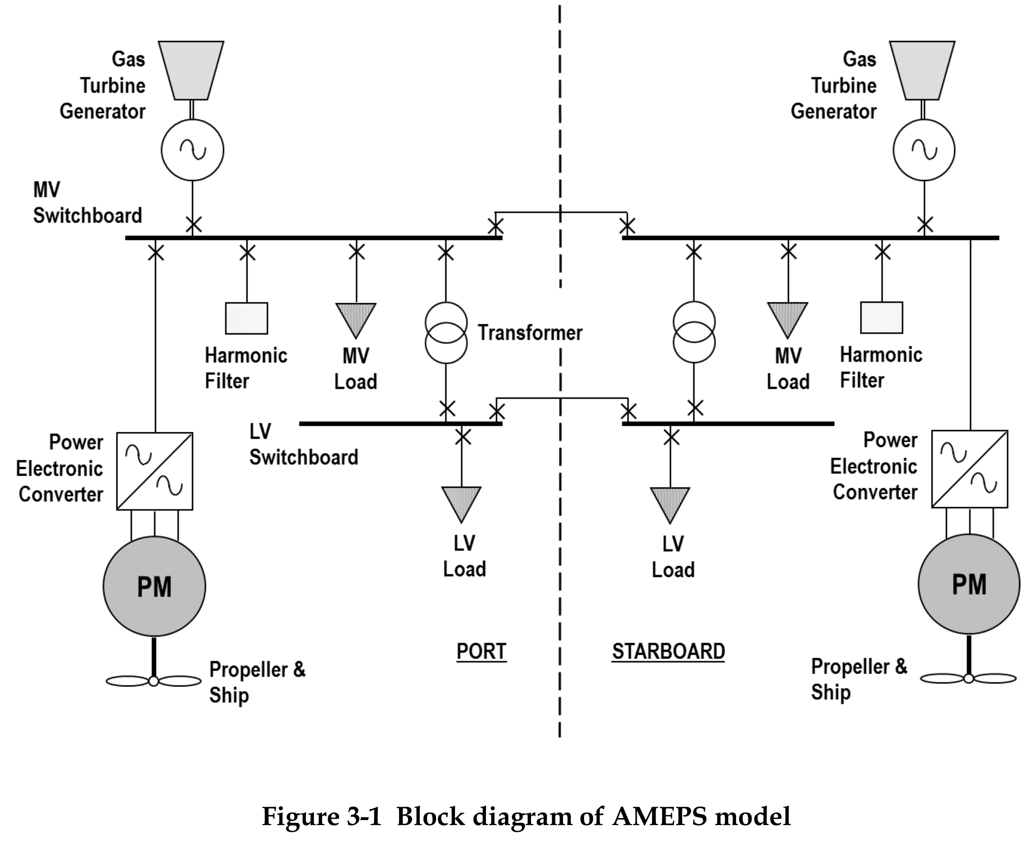


Figure 3-1 Block diagram of AMEPS model

The system parameters used for the AMEPS model have been summarised in Table 3-3, which are mainly based on the Type 45 Destroyer data available in the public domain:

Table 3-3 Network parameters AMEPS model

Subsystem	*Parameter value*
Generation power	2x Gas turbine, total 42MW
Propulsion power	2x Induction motors; total 40MW
MV voltage	4160 VAC, 60Hz
LV voltage	440 VAC, 60Hz
Vessel (deep load)	7350 tonnes

Figure 3-2 presents the *Matlab® /Simulink®:* implementation of the AMEPS model where the main submodels, such as the gas turbine & generator, electric drive & ship and the electrical distribution system have been highlighted. Each of these subsystems contains one or more layers. For example the control loops for the gas turbine were, as part of this thesis, modelled in the gas turbine submodel block. Figure 3-3 shows what is inside the gas turbine submodel block. This submodel contains the gas turbine model with governor control, the synchronous generator with exciter (AVR) control, a simulation initialisation block and measurement blocks. The electrical distribution submodel contains breakers and busbars. Cable impedances are (each little blue block is a single phase cable) connecting for example the electric drive to the electrical distribution subsystem. The fixed MV and LV loads were modelled using the load-blocks from the SimPowerSystems toolbox.

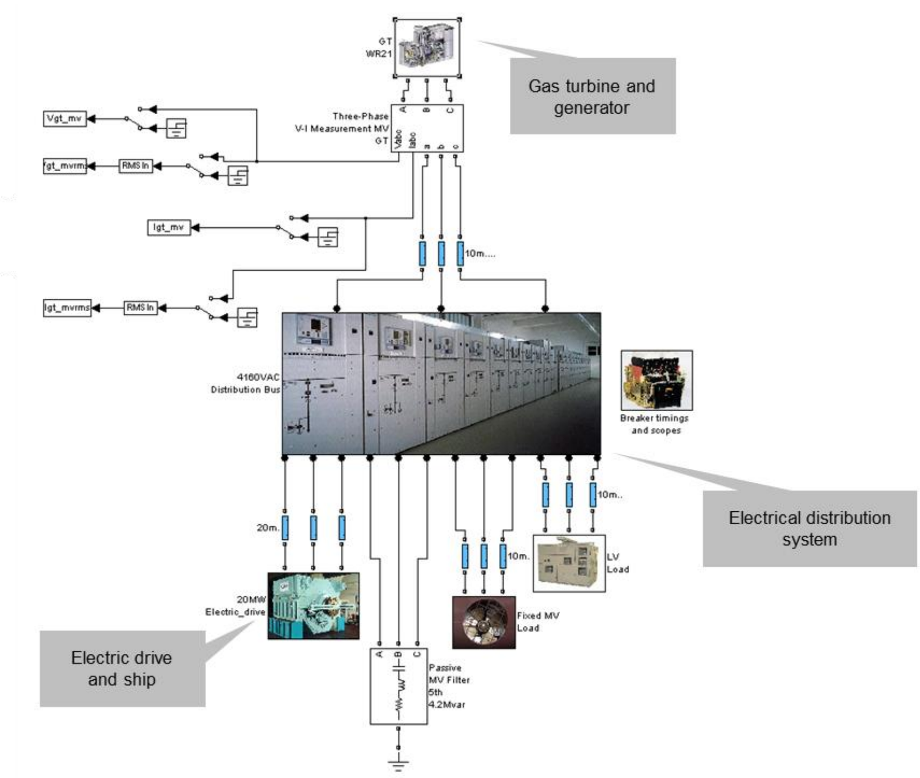


Figure 3-2 Implementation of AMEPS model in Matlab/Simulink

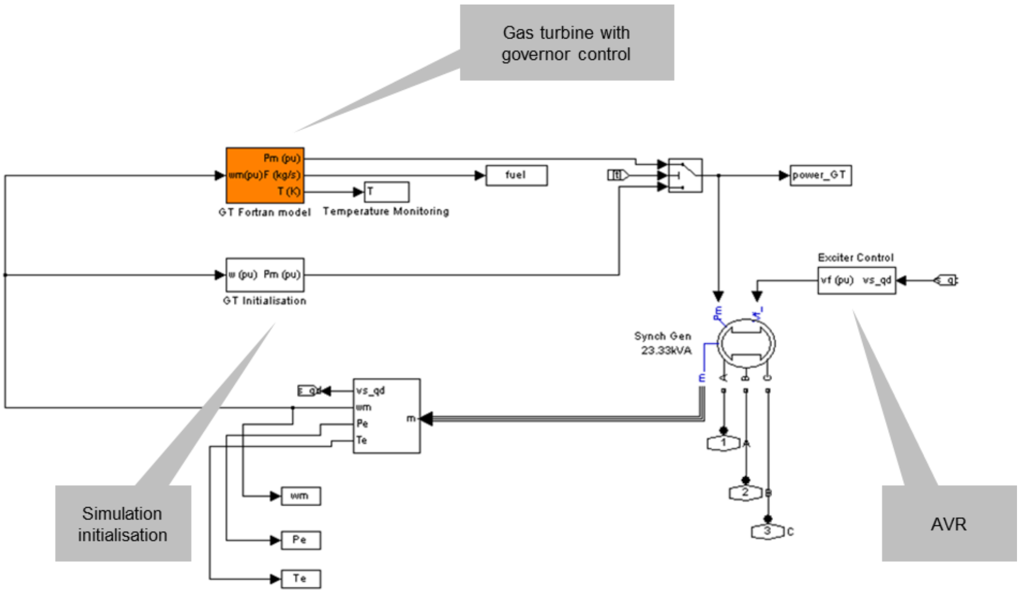


Figure 3-3 Model of gas turbine in Matlab/Simulink

3.4.2 IFEP models from literature

Over the years, several papers on modelling and simulation of marine power systems have been published of which key papers are summarized below. The advantages and disadvantages of each of the described methodologies with respect to the AMEPS model will be highlighted.

Monterrain [Monterrain03] reported on a modelling approach of DCN (since 2007 known as DCNS (Direction des Constructions Navales Services)) for the French Electric Ship programme. The programme includes the ELENA project, which has the objective to assess the characteristics and feasibility of a full electrical propulsion frigate. Typical radial marine power system network architecture was modelled in the Matlab®/Simulink® environment together with additional tool boxes including SPS. A number of challenges have been addressed in this paper including model validation, model fidelity and execution time.

Bennett *et al*. [Bennett07] and Norton *et al*. [Norton07] argued that modelling and simulation can benefit the development of marine power systems, both from a design and in-service support point of view. For example, modelling and simulation can be used to assess the effect of system upgrades, de-risk sea trials or it can be used as a means to diagnose system faults. It is expected that in-service support like modelling and simulation, results in significant cost-savings, effective planning and increased system understanding. This paper uses the DEF STAN 61-22 standard (Definition of Modelling Standards - Marine Electrical Power Systems) [MOD07] for two projects, which includes the modelling and simulation of the IFEP systems on board an Auxiliary Oiler (AO) and a LPD vessel. Model accreditation was used to assess the performance of the models.

Darengosse and Lars [Darengosse07] reported on developments in modelling and simulation of marine power systems and in particular marine electrical power systems. Specific modelling and simulation tools have been developed for a number of naval projects. The types of propulsion for these projects include mechanical, hybrid and electrical. A project discussed in Darengosse and Lars [Darengosse07] includes the FREMM (Frégate Multi-Mission) project of which the first vessel was commissioned in 2012. In 2013 a paper by Sulligoi *et.al* [Sulligoi13] was published in which the new FREMM electric Integrated Power Systems (IPS) was demonstrated. This time-domain simulator is used to study electromechanical transients in which low-fidelity models are used in order to run the simulation at a single time-step of 1ms.

Reference [Huang07] describes a distributed simulation approach by the Mississippi State University whereby a shipboard power system is split-up into several parts from, which then the dynamics will be evaluated concurrently. For complex systems including marine electrical power systems, such a distributed simulation approach will reduce the execution time as the computational simulation load is now shared across multiple processors. This distributed simulation approach allows parts of the system to be simulated concurrently even though the processors are geographically in different locations. The challenges are in how to partition (decouple) the overall model and how to deal with communication latency between the several processors. The Mississippi State University has used a VI overlap-decoupling method, which was initially implemented into Matlab® and later on into the Virtual Test Best (VTB).

Chalfant and Chryssostomidis [Chalfant11] mentions that the ESRDC is performing investigations into the dynamic performance of various IFEP power system architectures. This includes Medium-Voltage AC (MVAC), Medium –Voltage DC (MVDC) and High-Frequency AC (HFAC). These dynamic performance studies are conducted on both high-fidelity and low-fidelity models. The former are used for fault detection studies and the latter for developing overall architectural models in which multi-domain models are used. However, to the best knowledge of the author, only recently a paper was published for the marine shipping industry in which other researchers (also part of the ESRDC) - Thirunavukarasu *et al.* [Thirunavukarasu13] - demonstrate a modelling and simulation approach, which captures the interactions between the electrical system and a gas turbine. As opposed to the AMEPS model, the model in the paper is simulated with a single time-step of 1ms. A single time-step can be applied as the model does not contain a high-fidelity electric drive model, which requires a smaller time-step than 1ms.

3.5 Challenges for multi-domain modelling and simulation

3.5.1 Multi-disciplinary teams

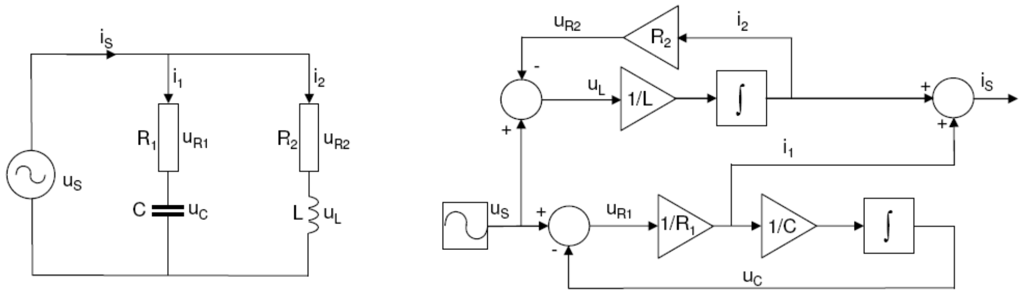
Several key preconditions need to be met in order to develop an integrated-model successfully. From an organisational point of view this includes the deployment of multi-disciplinary teams with the required subject-matter-experts (SME). A discipline in this context has extensive knowledge in a domain such as the mechanical engineering domain [Nikolic07]. As discussed by Schulten [Schulten05] it is essential that the communication between the different SMEs [Law07]) is unambiguous. For example one needs to agree on model boundaries, inputs/outputs and structures.

The AMEPS model was developed under a research consortium in which several academic and industrial partners collaborated. Each partner had extensive knowledge and experience in one of the physical domains present in the IFEP AMEPS model. Model boundaries and input/output variables were clearly defined. These input/output variables were defined according to "power conjugate" variables (more details on this in the next sections).

3.5.2 Model causality

The most popular modelling approach is the causal (alternatively block-oriented) approach where the equations describing the physics must be written in such a way that the direction of the signal flow (causality) is explicit. This means that the execution order of the functions (called blocks in Simulink®) must be known prior to the simulation.

For example consider Figure 3-4a, which represents the physical layout of an electric circuit adopted from [Nilson03] where u_s and i_s represent the source voltage and current respectively. Branch 1 consists of resistance R_1 in series with capacitor C whereas branch 2 consists of resistance R_2 in series with inductance L. Figure 3-4b shows the same electric circuit where u_s is the input and i_s the output. However, as opposed to the physical layout the electric circuit is represented in a causal block diagram (similar to that of Simulink®). The ODEs describing the circuit are listed in (3.1) and can be solved fairly straightforward using numerical integration methods.



a) b)

Figure 3-4 Causal system

$$\begin{aligned}
u_S &= u_{R1} + u_C = u_{R2} + u_L \\
i_1 &= \frac{u_{R1}}{R_1} \\
u_C &= \frac{1}{C}\int i_1 dt \\
u_{R2} &= R_2 i_2 \\
i_2 &= \frac{1}{L}\int u_L dt
\end{aligned} \tag{3.1}$$

Although it is evident from the given example that the causal model does resemble the electric circuit functionally, the causal model does not resemble the electrical circuit in terms of physical layout. Therefore translating a given system from a physical layout into a causal model requires some work [Nilson03]. Zgorzelski and Cameron [Zgorzelski98] mentioned that because a causal model only sees the effect of a specific input to the model, conclusions about the system behaviour cannot be drawn. Therefore multiple causal models, each with different inputs, are required to capture the entire behaviour of the system. This can be illustrated [Nilson03] by applying Ohm's law to resistance R_1 in Figure 3-4. As the behaviour of the resistor can be described by (3.2) and (3.3), two separate causal models must be constructed in order to completely capture the behaviour of the resistance.

$$i_1 = \frac{u_{R1}}{R_1} \tag{3.2}$$

$$u_{R1} = R_1 i_1 \tag{3.3}$$

Causal model are therefore not always easy to understand and reuse of the model can be bothersome.

Another modelling approach [Nilson03] is known as acausal modelling where the signal flow is implicit. This means that the execution order of the functions is not known prior to the simulation. As opposed to the causal model, the acausal model can be expressed in a format that directly reflects its physical structure [Nilson03]. Referring to the example of the resistance [Nilson03], for an acausal model this can be expressed as:

$$\begin{aligned} &u_{R1} = u_p - u_n \\ &i_p + i_n = 0 \\ &u_{R1} = R_1 i_p \end{aligned} \tag{3.4}$$

where subscripts p and n refer to the respective positive and negative pin of the component. As acausal languages support component hierarchy, components can be reused. In order to solve these acausal systems, considerable symbolic processing of the model is required. Although implicit DAEs can be solved with dedicated numerical methods, these are limited to DAEs of index 1. Reduction techniques of higher-index DAEs to index 1 are employed to use the numerical methods for implicit DAEs [Nilson03].

The electrical systems in the AMEPS model were developed using the components, which are available in the Matlab®/Simulink® toolbox SimPowerSystems. These components provide already an acausal modelling environment.

3.5.2.1 Bond graphs

In the bond graph modelling approach, the concept of energy exchange as an interaction between physical subsystems is considered. This approach has been used worldwide since Henry Paynter devised this method at MIT in 1960 [e.g. Borutzky99, Shiva04, Sjöstedt09 and Zupančič11] and is inherently acausal [Zgorzelski98]. In bond-graphs a graphical method is used to describe the energy exchange within physical systems. Energy can flow from one place to another, it can be converted into other forms of energy (mechanical, electrical, thermal, etc.) or it can be stored. However, energy cannot be dissipated. Therefore if the amount of energy changes, energy is either moving in or out. Energy changes with respect to time, which yields power P.

$$P = \frac{dE}{dt} \tag{3.5}$$

Power can be expressed as the product of (power) conjugate variables; effort *(e)* (variables that are measured with a gauge connected in parallel to an element) and flow *(f)* (variables that are measured with a gauge connected in series to an element), equal power [Shiva04, Zgorzelski98, Sjöstedt09]. For example the product of voltage *(v)* and current *(i)* is power.

$$P = v.i \tag{3.6}$$

These *effort-flow* variables are also referred to as *potential-flow* (Modelica[10]) and *across-through* (Simscape[11]) [Sjöstedt09]. One of the key features of bond-graphs is that different physical domains can be described by the same building blocks such as inertia, transformer and gyrator. In Table 3-4 the power conjugate variables for a number of different domains are presented.

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[10] Modelica software tool

[11] Simscape is a toolbox of Matlab/Simulink

Table 3-4 Power conjugate variables

Domain	*effort (e)*	*flow (f)*
Electric	Voltage (u)	Current (i)
Mechanics	Force (F)	Velocity (v)
Rotation	Torque (M)	Angular velocity (ω)
Hydraulic	Pressure (p)	Volume flow (q)
Thermal	Temperature (T)	Entropy flow (S)

Power conjugate variables were used in the AMEPS model as this approach enabled acausality and easy coupling between different domains.

3.5.2.2 Block oriented modelling

Most simulation software assumes that a system can be decomposed into a block diagram structure, which relies on causal interaction [Zupančič05]. For example the Matlab®/Simulink® simulation tool can be classed as a block-oriented simulation language [Navarro00, Nilson03, Zupančič05 and Casella05]. Due to its causal nature (uni-directional energy flow), block oriented modelling is considered not suitable for modelling an integrated-model, which requires acausality (bi-directional energy flow).

Some parts, as for example the diesel engines in the network architecture study in Chapter 5, were modelled in a causal way as that was considered to be an appropriate solution for that particular model. In that case the study objective was to consider only maximum fault current levels, voltage dips, etc. Investigating the bi-directional interactions between different submodels/domains was not considered here.

3.5.2.3 Object oriented modelling

Object-Oriented Model (OOM) has become more and more popular for modelling multi-domain systems. A number of features characterise OOM, which includes instantiation, inheritance and encapsulation [Borutzky99, Law07]. Since the late 90s standardisation has been going on to combine features of several modelling languages into a unified OOM language known as Modelica [Borutzky99]. In an OOM, each physical component is described by a set of equations, which describes how the physical component behaves [Sjöstedt09]. These equations could include DAEs, ODEs and event-triggered difference equations. As a result, the boundary conditions of the model are not necessarily defined a-priori as input or output signals. Therefore, this (acausal) model of the physical component is always the same regardless of what is connected to it. Therefore, this approach is fundamentally different from a block-oriented modelling approach (causal model) in which the model has defined input and output variables [Casella05].

3.5.3 Algebraic loops

Generally models, including models of multi-domain systems, may contain several feedback loops between the different subsystems. As such, in those feedback loops algebraic loops may occur. Norman *et al*. [Norman08] defined and formalised the occurrence of algebraic loops as follows. If a feedback loop only contains functions without memory, an algebraic loop occurs. Effectively this means that the input to a function is an implicit function of the output of that same function. In Simulink®, such functions are said to have the direct feed-through property [Mathworks07]. Algebraic loops can be formally expressed as [Norman08]:

$$y(t) = f(x, y(t)) \tag{3.7}$$

where y and f are continuous real valued functions of t. A simple example of an algebraic loop is shown next:

$$y(t) = k_1 x(t) - k_2 y(t) \tag{3.8}$$

where k_1 and k_2 are constants and $x(\cdot)$ is a continuous real valued function of variable t. The dependency of $y(t)$ upon itself is evident in this equation. In the case of (3.8), a simple rearrangement will express the equation in standard form, giving

$$y(t) = x(t)\left(\frac{k_1}{1 + k_2}\right) \tag{3.9}$$

However, within multi-domain models, more complex functions and loops exist, which cannot be solved to yield feedforward equivalent solutions in a straight forward way. Instead, additional solver algorithms must be employed to find an approximate solution [Norman08, Sjöstedt09].

The Matlab®/Simulink® software for example contains iterative algorithms to solve the algebraic loops present within this model. Typically, the algorithms employed use a rearrangement of Newton's method. However, the additional calculations performed by these solver algorithms lead to a significant decrease in the computational speed of the simulations conducted [Norman08, Sjöstedt09]. Additionally, there is the risk of failed simulations if these algorithms fail to converge on a solution within a predefined number of iterations (put in place to avoid simulations running indefinitely). These outcomes are clearly unacceptable for multi-domain models, which are already very computationally demanding. As such, alternative solutions must be employed to negate the negative effects of the algebraic loops.

For example small delays could be employed within multi-domain models (typically of the order of one time-step) in order to remove the algebraic loops. In this manner, the data fed around the loop is delayed and the input of a particular function now becomes dependent on its own output from the previous simulation time-step, effectively breaking the direct feed-through of the loop. Applying this solution method to (3.8) yields [Norman08]:

$$y(t)=\begin{cases}k_1x(t) & \text{for } t=0\\ k_1x(t)-k_2y(t-1) & \text{otherwise}\end{cases}\tag{3.10}$$

(3.10) illustrates how variable *y(t)* is no longer a function of itself at the same time instant. As such, the insertion of a small delay has successfully removed the algebraic loop. This method for removing algebraic loops is both easily implemented and very effective. Yet, care must be taken in the utilization of these delays as they may compromise its numerical stability [Sjöstedt09]. This can be demonstrated by considering the general solution of (3.10), which yields [Norman08]:

$$y^{(N)}=k_1x\sum_{i=0}^{N}(-1)^i k_2^i\tag{3.11}$$

For this solution to be numerically bounded, it is necessary that $|k_2| \leq 1$. If this condition is not met, the behaviour of the delayed function will not be representative of the un-delayed original. Additionally, if the magnitude of k_2 is suitably large enough (whilst remaining less than unity), this will result in oscillatory behaviour from the function, which again will be a poor representation of the original function. Typically, the solution of recurrence equation of the type given by (3.7) can be readily solved using either algebraic or numerical techniques. However, the complexity of the algebraic loops found within multi-domain models effectively prevents an assessment of their numerical stability. Instead, there is a need for careful interpretation of the simulation results produced in order to determine the validity of these. This is especially true given that the limits of numerical stability associated with this model will change with variations in network state and operating conditions (i.e. with the same effect as varying k_2 in (3.10) above). For example, the model may be numerically bounded and well damped for a load change transient, but very oscillatory and completely inaccurate under electrical fault conditions [Norman08].

Delays of one time-step (*t-1*) were applied to the AMEPS model wherever feedback loops without memory were present. The stability of these delays was not explicitly assessed mathematically as the functions describing the AMEPS model cannot be solved analytically. However, simulation results of the AMEPS model were face validated and showed no sign of instability.

3.5.4 Multiple time-scales

E and Engquist [E03] reported on the rapidly evolving research area of multiscale modelling and computation where multiscale refers to either multiple time - or multiple spatial-scales. Conventionally multiscale research has been studied in mathematics where techniques such as Fourier analysis and wavelets have been used. Other techniques include multi-grid, domain decomposition and multi-resolution. Due to the nature of problems in applied sciences and engineering, the study of multiscale problems have become of interest to researchers in these fields. Examples of typical multiscale problems in the spatial domain include mass distribution in the universe and turbulent flows [E03]. Typical examples of multiple time-scales can be found in the field of biology, geophysics, physics [Fujimoto03], chemistry [Brackbill85] and engineering. For example biological rhythms could include multiple time-scales ranging from days down to sub seconds [Fujimoto03]. Another example includes electrical power systems, which often have time-scales ranging from microseconds for power converters up to several second for the dynamics of prime movers [e.g. Pekarek04 and Kato06]. As the focus of this thesis will be on assessing the dynamical system behaviour with respect to time, hereafter multiscale is only used in the context of multiple time-scales.

A key challenge facing the development of an integrated-model, which represents a complex multi-domain system, is often the multiscale nature of such a system. In the context of this thesis, a multi-domain system implies a system of a multiscale nature and vice versa. Typically these multiscale systems will contain both slow (latent) and fast (active) subsystems [Chen04]. Slow subsystems can be characterised as a system having large time-scales, slow varying state variables and small eigenvalues. In contrast, fast subsystems have small time-scales, fast varying state variables and large eigenvalues. Multiscale systems described by differential equations are also termed stiff [Pekarek04, Word07]. Table 3-5 shows the wide variety of time constants that can be found in a typical IFEP system.

Table 3-5 Typical IFEP time constants

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

Simulating these systems will result in a substantial computational burden [Crosbie07, Norton07] and hence a reduction in computational efficiency (i.e. excessive simulation execution time). In Uriarte and Butler-Purry [Uriarte06] it is mentioned that factors affecting the execution time include computer hardware, discretisation method, time-step, model fidelity, programming efficiency and other programmes running in the background.

The differential equations present (e.g. ODEs and DAEs) in a model, are solved by dedicated numerical integration methods (sometimes referred to as solvers). A suitable time-step (sometimes referred to as solver time-step, integration time-step or simulation time-step) for these numerical methods needs to be used. Often this is a trade-off between simulation accuracy, numerical stability and computational efficiency. For example simulating high-fidelity power converters models require very small time-steps, which could be in the in the order of microseconds [Gole97, Pekarek04].

Multiscale models may require significant computational resources in order to conduct simulations and may therefore increase the execution time. Two particular influences on these requirements can be identified [Gole97]:

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

Next, several methods will be discussed briefly, which may reduce the execution time and hence increase the computational efficiency. Note that some of these methods may be employed simultaneously.

3.5.4.1 Model abstraction

Subsystems, in particularly the fast subsystems, will be modelled at the minimum acceptable level of fidelity required to fully characterise the phenomena of interest. The level of fidelity can be specified on a subsystem-by-subsystem or even on a component-by-component basis [MOD07]. For example, when interested in the harmonics present within a power system, modelling the power electronics in detail may be required. However, modelling the loads of the power system in high-fidelity would be unnecessary (and undesirable as this increases the execution time (e.g. [Norton07])) in this case. Even so, Norton *et al*. [Norton07] mentioned that for complex systems, such as IFEP, there is little room to trade high levels of fidelity for reduced execution times if realistic results are to be obtained.

In terms of the AMEPS model, the rectifier in the propulsion drive was represented using a hybrid model [Apsley07, GonzalezVillaseñor06a] that utilises a detailed diode bridge rectifier model together with a state-space model of the DC-link. The inverter was represented as 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 time-step for the entire propulsion drive model, further improving the overall computational efficiency. 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.

3.5.4.2 Increased computational power

The characteristics of the hardware used in modelling and simulation affect the execution time [Uriarte06]. Therefore increasing the computational power reduces the execution time. Hebner *et al.* [Hebner10] mentions that the ratio σ of the execution time versus the simulated time on an off-the-shelf personal computer could be in the order of 100.000 -300.000. Furthermore it is unlikely that acceptable reduction in σ can be obtained by just utilising extra processing power - even if multi-core parallel computing on personal computers are used [Hebner10].

The idea of the AMEPS model was that it could run on an off-the-shelf personal computer without having to add extra processing power or memory or to rely on parallel computing. Therefore, reducing the computational burden was not driven from a hardware point of view.

3.5.4.3 Parallel computation and Model partitioning

Parallel or distributed simulation is referred to in [Zeigler00] as "a network of geographically dispersed simulators of model components to execute a single overall model". Parallel simulation can also be referred to as a computer containing more than one Central Processing Unit (CPU) [Blaise07]. There are a number of reasons where parallel simulation offers improvements in terms of a reduction in the execution time of the model. [Zeigler00]. The reduction in execution time increases with more dispersed simulators. However, this reduction is not proportional to the number of dispersed simulators [Hebner10]. In addition the combined memory capability of the simulators can be used for complex models. However, the implementation of parallel simulation is not straightforward. Although real world systems operate naturally in parallel, this is not easily employed in a parallel simulation network [Zeigler00]. Faruque *et al*. [Faruque09] proposes a distributed simulation where the electrical and thermal systems of AES are run on different simulation platforms at geographically different locations. These simulations are coupled by exchanging feedback signals. One of the major challenges with this is the communication latency and their effect on stability and accuracy of the simulation.

The literature describes a number of methods how a model can be partitioned into various segments. Moreira *et al*. [Moreira06] mentioned a number of partitioning strategies in the electric domain. This includes diakoptics, Modified Nodal Analysis (MNA) and Multi-Area Thevenin Equivalents (MATE). The idea of diakoptics was developed by Gabriel Kron in the 1950's, which is based on the idea that a large system (typically electrical systems) can be torn into several subsystems. Then each subsystem is solved in isolation (i.e. not taking into account the other subsystems). Next the solution for each subsystem is combined to obtain the overall system solution [Lai94]. Initially the idea of diakoptics was proposed (in the early 20th century there was no or limited computational power available) in order to break down a complex system in more manageable subsystems [Lai94]. Although welcomed and studied by many, diakoptics lost popularity in the 1970's due to the introduction and success of sparse matrix ordering techniques and MNA [Uriarte06]. However, diakoptics were found to be suitable for parallel computer applications [Lai94, Uriarte06]. In Martí *et al*. [Martí98] it is mentioned that subsystems within large systems, such as terrestrial power system, can be decoupled completely due to the existence of long transmission lines, which inherently are time delays. Norton *et al*. [Norton07] discussed system partitioning on board IFEP vessels where it is recommended to partition a system at the points of minimal interconnection and at the points of minimal signal bandwidth. By partitioning the system at these points, the state-space matrices of each part will be better conditioned than it is the case for the state-space matrix of the entire system. This will also increase the numerical stability.

For the AMEPS model parallel computation was not considered as the model had to run on off-the-shelf personal computers. Therefore model partitioning was not considered either. Instead, computational efficiency was obtained by applying multi-rate techniques (this will be discussed in Section 3.6 in more detail). However, combing multi-rate techniques with parallel computation and model partitioning will improve the computation efficiency even more, which allows even larger and more complex high fidelity multi-domain models to be investigated.

3.5.4.4 Numerical solutions

Fixed - and variable time-step integration methods have conventionally been used for power system analysis [Chen08]. As opposed to fixed time-step methods, with variable time-step methods the time-step size is adjusted dynamically during the simulation in accordance with the fastest subsystem. In essence this method is based on the fact that the time-steps have to be small during the activity of fast subsystems but is allowed to be larger during the integration interval where the slow subsystems are dominant. Automatically adapting the time-step to the solutions trajectory, avoids the use of unnecessary small time-steps. Therefore the computational efficiency is improved. For adaptive step-size control to be successful implemented, an estimate of the Local Truncation Error (LTE) for each step is required [Crow96, Chapra06]. However, there are several disadvantages when variable time-step methods are employed [Moreira06]. The latent behaviour of slow subsystems allows the time-step to increase. Nevertheless, if a system is considered falsely to be latent, errors may propagate to other subsystems thereby producing wrong solutions.

A stiff system involves differential equations with slow and fast varying components. However, often the solution is dominated by slow varying components for most of the integration interval. In contrast, fast varying components are often active for only a small fraction of the integration interval [Chapra06]. Examples of stiff systems are chemically reacting systems where chemical reactions occur at different time-scales [Ascher98] and power systems containing power converters and prime movers [Pekarek04, Yang07]. Literature such as Word *et al.* [Word07], Pekarek *et al.* [Pekarek04] and Ascher and Petzold [Ascher98] has reported that if for a stiff system, a too large a time-step is selected relative to the time-scale of the fast subsystem they will result in unstable solutions. This effectively means that a very small time-step (smaller than is required for the fast subsystem) must be selected. This is for example the case when popular integration methods such as the explicit Euler and Runge-Kutta algorithms are used. Instead other methods are conventionally used in case of stiff systems, which can be classified into two general categories: stiffly-stable variable time-step methods and time-scale separation methods [Pekarek04].

Numerical integration can be categorised into implicit and explicit methods. In explicit integration, next step state values are calculated using previous step state values [Yang07]. This can generally be expressed as:

$$x_{n+1} = g(x_n, x_{n-1}, \ldots) \tag{3.12}$$

where n represent the time-step. The form of function g will be different for the various integration methods. Examples of explicit integration methods include the one-step Forward Euler [Chapra06, Yang07], explicit Runge-Kutta and Adams-Bashforth method. Explicit integration methods are relatively fast but may cause numerical instability [Yang07]. Explicit fixed-step integration methods are an appropriate solution for real-time solutions [Thiele14]. In contrast, the next step state values for implicit integration methods are embedded in the equation itself as shown in (3.13) [Yang07].

$$x_{n+1} = g(x_{n+1}, x_n, ...) \tag{3.13}$$

Typical examples of implicit integration methods include the one-step Backward Euler, trapezoidal method, implicit Runge-Kutta, Adams-Moulton and Backward Differential Formulae (BDF) method [Chapra06, Yang07]. For the dynamic simulation of stiff systems, implicit integration methods are typically used [Pekarek04, Chapra06, Yang07,] although the explicit one-step Rosenbrock's method is stiffly-stable as well [Pekarek04]. Typical stiffly-stable algorithms include implicit Runge-Kutta and Gear's methods [Chapra06]. Although implicit integration methods offer good numerical stability, they are slow in performance.

With respect to the AMEPS model the fast subsystems produce fast dynamics for most of the integration interval. As a consequence the time-steps must remain small. This situation would not be much different from the single-rate method. Therefore hardly any computational benefits are obtained and hence alternative methods must be employed.

3.5.4.5 Multi-rate simulation

Conventionally, for simulations using numerical methods a uniform time-step (also known as single-rate) is applied to the entire model. Using a single-rate time-step should be adequate as long as the range of time constants within the model is limited or as long as the phenomena of the slow and fast subsystems do not occur simultaneously. However, using a single-rate approach is computational inefficient for multiscale systems where slow and fast subsystems may be active simultaneously. This is due to the fact that a time-step must be chosen appropriate for the fastest subsystem, which corresponds to the system with the smallest time-step. For systems solved with explicit integration methods these time-steps must be small enough to maintain system-wide stability [Thiele14]. As a consequence these small time-steps are also taken for the slower subsystems. However, these small time-steps are unnecessary for the slower systems and will therefore reduce the computational efficiency [e.g. Moreira06 and Chen08]. One method that could be employed in order to improve the computational efficiency of multiscale models is to divide the model into two or more segments where each segment contains submodels of similar time-scales (similar dynamic behaviour). Next each segment is solved at a time-step that is most appropriate for the segment's dynamic behaviour. This method is called multi-rate simulation (sometimes referred to as multiple frame rate [Crosbie07]). In addition to different time-steps each segment could also use a different integration method [e.g. Word07 and Thiele14]. However, multi-rate simulation may have a negative impact on the simulation accuracy due to error propagation. Therefore, Section 3.6 has been devoted to this topic.

This method was applied to the AMEPS model due to the presence of for example power electronics (fast subsystems) and vessel dynamics (slow subsystems), which act simultaneously.

3.5.5 Model validation, verification and accreditation (VV&A)

Concern exists among model developers, users and policy makers whether a model is correct in the sense that it represent the actual system of interest accurately within a certain bandwidth. Therefore this section will discuss the key principles on model Validation, Verification and Accreditation (VV&A).

The main focus however, for the remaining of this thesis will be on validation of models.

Law [Law05] defined validation of a model as a process to determine whether the model is an acceptably accurate representation of the system within the context of the objectives of the study in which it is applied. This process is described by Law [Law07] as one of the most difficult tasks in the modelling process. A model should be designed and developed to address one or more questions, which are understood in advance; this also specifies the level of fidelity required in the model [Law05, Sargent03].

Figure 3-5 presents a modelling process as described in [Sargent03]. The *system* in this figure represents the system or a phenomenon that needs to be modelled. The *conceptual model* represents the mathematical/logic/verbal description of the system. When the conceptual model is implemented in a computer programme, a *computerised model* is obtained. The dotted lines indicate the validation and verification processes. In reference [Sargent03] these processes are defined as follows. The conceptual model validation assesses whether the underlying mathematical/logic/verbal representation and assumptions are reasonable with respect to the purpose of the model. The computerised model verification assesses whether the conceptual model is correctly implemented into the computerised model. The operational validation assess whether the outputs of the computerised model has sufficient accuracy to represent the system. Usually this modelling process is an iterative process until a sufficient valid model is obtained.

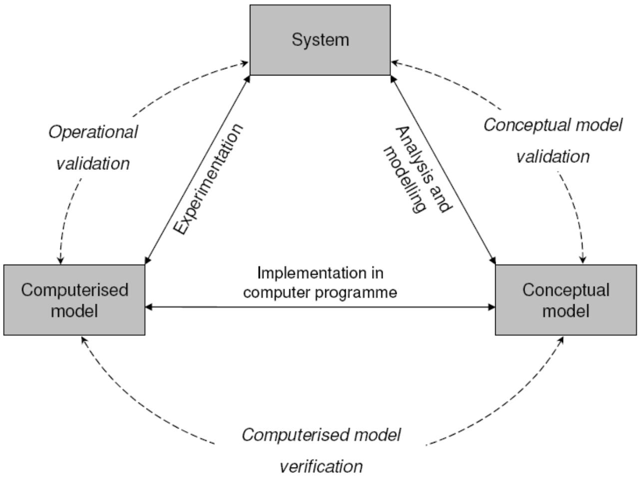


Figure 3-5 Modelling process

Different validation techniques exist including the comparison to other models, event validity, extreme condition tests, face validity, traces, and parameter variability – sensitivity analysis, which are mentioned in [Sargent03, Law07] amongst some other techniques. Commonly, a number of validation techniques are employed together to provide greater levels of confidence. A number of these techniques, discussed in more detail below, were selected for the AMEPS model validation as these were found most suitable.

3.5.5.1 Comparison to other models

The simulations responses of the model, which are to be validated, are compared with the results of other previously-validated or independently constructed models.

The rectifier hybrid model of the AMEPS propulsion drive model was validated against an equivalent model constructed using the PLECS piecewise linear element circuit simulation tool [Plexim08].

3.5.5.2 Face validity

In this approach, opinions are sought from one or more domain experts (i.e. SMEs) as to the acceptability of the model's construction and/or the behaviour it predicts. No formal method is used here, the model is only judged on the basis of face appearance. General model behaviour can be validated by this method. Therefore, face validation can be considered as a qualitative method rather than a quantitative method. Generally face validation is considered to be useful during the early stages of the design. With relatively methods, obvious errors and inconsistencies can be spotted and fixed. However, more rigorous validation methods are required for a complete VV&A [Illigen01]

The propeller model of the AMEPS 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 marine shipping industry was obtained. This assistance was particularly valuable in validating the underlying mathematical assumptions and in interpreting the results generated.

Models of the AMEPS electrical network components were mainly validated using face validation. Also, the components in the SPS toolbox have been derived from textbooks and are validated by Power Systems Testing and Simulation Laboratory of Hydro-Québec [Mathworks08].

3.5.5.3 Predictive validation

In this method, simulation results are compared against measurements made in the field obtained by experiment either from existing systems or test-rigs. Such a method would obviously be very helpful for model validation. However, obtaining field data may be difficult as data is often subjected to confidentiality agreements. Also, as the systems under consideration are often still in the design stages, no field data is available yet. The use of test-rigs may be an attractive alternative but at the same time may be very costly and time consuming. As a consequence this will negate the economic benefits of using an integrated-model in the design stages. In addition test-rigs are also limited in the number of subsystems and configurations that can be tested.

For the propulsion motor subsystem of the AMEPS model, predictive validation was used by comparing the simulation results against the result of a test-rig [Apsley07]. Figure 3-6 shows an example of this comparison study, 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 3-6 demonstrates the accuracy of the motor model.

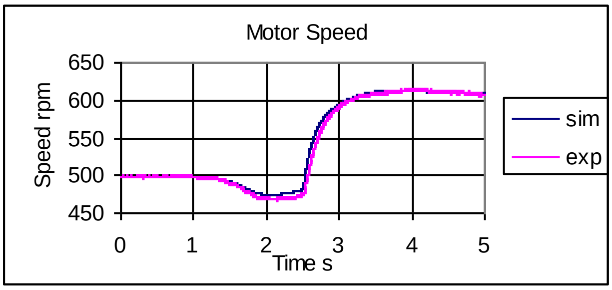


Figure 3-6 A comparison of experimental and simulation motor speed

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

3.5.5.4 Validation of an integrated-model

Despite the fact that individual subsystems may have been validated using various validation methods, the integrated-model may still benefit from an additional system-wide validation. For example non-trivial system behaviour, due to complex subsystem interactions, can only be validated by considering the system as a whole. Unfortunately system-wide model validation is not straightforward. As described previously, predictive validation with test-rigs for subsystems may not always be possible due to time and cost constraints. This is even more of a challenge for predictive validation of an entire system.

As an alternative model accreditation according to MoD modelling standards [MOD07] can be applied in which face validation is used to validate the integrated –model. Although this model is an inherently subjective approach, this is perhaps the best practically achievable solution in light of the limitation as discussed. The overall system behaviour of the AMEPS model was validated by face validation where a number of different industrial (SMEs) and academic experts reviewed the results.

3.6 Multi-rate simulation

The multi-rate method was first proposed by C.W. Gear in 1974 in a report called *"multirate methods for ordinary differential equations"* [e.g. Crow94, Chen04, and Chen08]. In 1994 a paper submitted by Crow and Chen [Crow94] was one of the first to discuss the potential use of multi-rate for analysing power system dynamics. The reason for the increased interest of multi-rate for power system simulation was that variable time-step methods are ineffective if devices such as induction motors (with continually changing loads) and power electronics are included in the system [Crow94].

Due to limited computational power, multi-rate methods were applied in the past to speed up simulations. With increasing computational powers over the years, the need for multi-rate methods decreased [Huang07, Word07]. However, recently there has been a resurgence of interest for multi-rate methods due to a number of factors. For example systems have become increasingly more complex. In addition, some applications require multiple simulation runs (such as multi-objective optimisation). Both examples require more efficient simulation methods when excessive execution times, and hence reduced computational efficiency, is to be avoided [Word07]. Finally, real–time simulation of some systems, such as power electronics and automotive engines, require time-steps of a few micro seconds or even less. This type of real-time simulation is referred to as High-Speed Real-Time (HSRT) [Crosbie07]. As many of the present real-time simulators have an uncertainty or jitter between 5 and 10μs, these are considered not to be suitable for HSRT simulations. Therefore expensive special hardware and software must be employed. As these systems usually also contain subsystems, which can handle larger time-steps, multi-rate methods are of particular interest for HSRT simulations [Word07, Bednar07, Crosbie07]. However, it has been recognised by Pekarek *et al*. [Pekarek04] that it has often not been a straight forward task to employ multi-rate simulation using modelling languages. This is due to the fact that integration algorithms cannot always be modified such that it can handle multiple time-steps simultaneously. This meant that general-purpose languages such as C, C++ and FORTRAN had to be considered. However, presently modelling languages such as ACSL, EMTP (The Electromagnetic Transients Program) [Pekarek04] and Simulink® [Schuddebeurs10] allows the employment of a multi-rate simulation. The author acknowledges that other modelling languages may have similar multi-rate simulation capabilities as well.

3.6.1 Advantages of multi-rate simulation

3.6.1.1 Theoretical background

For simplicity but without loss of generality, two subsystems will be considered here to demonstrate the concept of multi-rate simulation. Figure 3-7 illustrates the execution sequence for a slow (s) and fast (f) subsystem with their respective macro (h_s) and micro (h_f) time-step where $h_s > h_f$. Time-steps h_s and h_f can be defined as the respective time interval [S_t, S_{t+1}] and [F_t, F_{t+1}] The ratio m between h_s and h_f can be expressed by (3.14).

$$m = \frac{h_s}{h_f}, \quad m \in N \middle| m > 1 \tag{3.14}$$

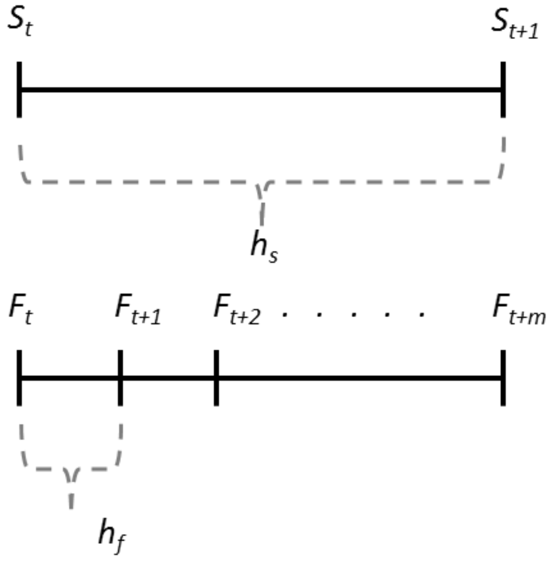


Figure 3-7 Multi-rate concept

Consider two connected subsystems, operating at different timescales whereby the output of the slow subsystem is the input for the fast subsystem. Synchronisation of the solutions takes place after each completed time interval h_s. In order to calculate the intermediate values for $F_{t+1}…F_{t+m-1}$, a number of approaches can be applied. This includes Zero Order Hold (ZOH), First Order Hold (FOH) and linear interpolation [Huang07, Word07]. In contrast consider two connected subsystems where the output of the fast subsystem is the input for the slow subsystem. The fast varying values from the fast subsystem at $F_{t+1} \ldots F_{t+m-1}$ should be averaged in some manner before it can be used as an input for the slow subsystem at S_{t+1} [Huang07, Word07].

3.6.1.2 Multi-rate application for the AMEPS model

Three significantly different time-steps were used in the AMEPS model and applied to the several subsystems. These time-step and associated subsystems are listed in Table 3-6. The discrete simulation method was used in the Matlab®/Simulink® environment to run the simulations.

Table 3-6 Time-steps AMEPS model

Time-step	*Subsystem(s)*
5µs	Electric system, propulsion motor
400µs	Electric drive (inverter)
1ms	Gas turbine, propeller and vessel

Table 3-7 illustrates a typical reduction in model execution time when using the multi-rate method compared to the single-rate method. The results are obtained from simulations with the AMEPS model and are the arithmetic mean of three separate simulations (Case *D* was only simulated once). The platform used for the simulations had an Intel Pentium 4 processor with a CPU of 3 GHz and a RAM capacity of 3.49 GB. In this table the *execution time ratio (X)* is the ratio of the single-rate execution time over the multi-rate execution time. As the gas turbine model had to be simulated with fixed time-steps, a fixed time-step multi-rate approach was adopted.

Table 3-7 Comparison of single-rate vs. multi-rate

Case	*Simulated time (s)*	*Single-rate (s)*	*Multi-rate (s)*	*Execution time ratio (X)*
A	1	2030.1	97.4	20.8
B	3	4507.1	283.1	15.9
C	5	7970.2	526.1	15.1
D	3	5012.7	538.4	9.3

In order to run the AMEPS model in single-rate multiple times, the high-fidelity electric drive and propulsion motor model was replaced by a fixed load of similar power capacity (cases *A*, *B* and *C*). However, to see how long the full AMEPS model (including the high-fidelity electric drive and propulsion motor) would run in single-rate, case *D* was used. Based on one simulation run for case *D* a calculated *X* value of 9.3 was obtained. For the cases *A*, *B*, and *C* values of *X* between 15 and 21 were observed. The lower *X* value for case *D* compared to the other cases is due to the fact that a relative higher portion of the AMEPS model must be simulated at the smallest time-step. From this study it can be concluded that multi-rate offers a significant reduction in execution time when compared to single-rate simulations.

3.6.2 Errors in multi-rate simulation

3.6.2.1 Introduction

Employing a multi-rate simulation method for multiscale systems has the potential to increase the computational efficiency significantly. However, at the same time there are a number of challenges that needs to be addressed. For example, a several papers have discussed stability issues of multi-rate simulation methods. In Bednar and Crosbie [Bednar07], Crosbie *et al.* [Crosbie07] and Chen *et al.* [Chen04] factors are discussed that affect the accuracy and stability of a simulation employing multi-rate. These factors include the time-step used, ratio *m*, numerical integration method and the communication method between segments (data transfer).

Sørensen *et al.* [Sørensen14] published a paper on the application of multi-rate simulation for reefer container dynamics. In their study they conducted a quantitative investigation in which for example the errors between a single-rate and multi-rate simulation were assessed. Also the effect of the Matlab® ode15s and VS-FE (variable-step and forward-Euler) solver in combination with multi-rate simulations on the associated errors were investigated. In their research Sørensen *et al.* observed that the VS-FE in combination with a multi-rate approach is faster than the ode15s without increasing the error. Their final conclusion is that it is important to use a solver with a low computational overhead, when using multi-rate simulation, as the time-steps are too short for an advanced solver to reach its true potential. With multi-rate simulation speed improvements of 3,5 times were achieved.

So far multi-rate simulation research has hardly considered the propagation of errors when multi-rate simulation is used. Assessing these errors, in particularly in systems with feedback and feedforward loops, provide valuable insights in how to judge the simulation results. An important factor is the manner and location in which data is transferred from slow subsystems to fast subsystems and vice versa. These error propagations will be the main focus for the remainder of this chapter and was reported in several publications including [Schuddebeurs8a, Schuddebeurs8b, Schuddebeurs8c and Schuddebeurs10].

3.6.2.2 Latching

In a multi-rate model where data from a fast to a slow subsystem is transferred, transient phenomena from the fast subsystem may be inadvertently amplified. To avoid this risk, data transferred must be reflective of the average situation over the longer time-step rather than that at the instant of synchronisation [Pekarek04,Crosbie07,Sørensen14].

For example, consider a case in which a transient effect of short duration, perhaps a voltage spike in an electrical system lasting for a few time-steps h_f, occurs in a fast subsystem. This fast subsystem is connected to a slow subsystem, which is simulated with a much longer time-step h_s. 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. Sørensen *et al.* [Sørensen14] reported in their study that the errors due to the use of ZOH delays are not critical for control experiments because these delays are much smaller than the dominant dynamics (e.g. the thermal masses of the evaporator and condenser). In addition under normal operation the system is in steady-state condition for most of the time. Therefore, ZOH delay errors due to latching of transients have little impact on the long-term simulation accuracy. However, because of the following reasons this conclusion by Sørensen *et al.* may not be true for complex systems such as IFEP:

- The latching error may provoke, through the control loops, different responses from other parts of the system compared to a latching-free case. This phenomenon, not considered by Sørensen *et al*, is explained in more detail later on in this section.
- The latching error in systems with power electronics and mechanical components may have a larger ratio m than the reefer container model. Assuming the same order of magnitude for h_s but a much smaller order of magnitude for h_f, the latching error may be significantly more than the errors reported in Sørensen *et al.*

This latching phenomenon for complex multi-domain system such as the AMEPS model is illustrated in Figure 3-8, 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 h_f, whereas the inverter runs at a much longer time-step h_s. 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.

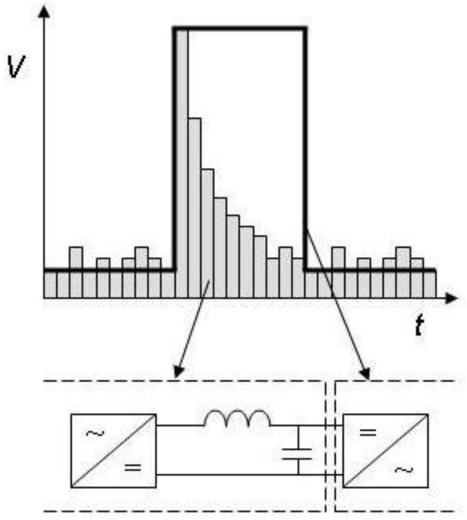


Figure 3-8 Latching between DC-link and inverter

Given the large time-step differences (large m ratio) 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 instantaneous load changes in certain parts of the network are likely to lead to problems of this nature, with consequently inaccurate simulation of the behaviour of slower-responding components such as the gas turbine.

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.

3.6.2.3 Filtering

Averaging of the fast subsystem signal is required in order to prevent the latching phenomena to occur. Averaging could be achieved either through some sort of artificial filter or by utilising some form of inherently available system inertia. In case of inherently available inertia in the system no or less artificial filtering is required. Therefore the behaviour of the model will be closer to the behaviour of the system that it represents, i.e. no artificial source of error is introduced in the simulation. This type of filtering has also been recommended in literature. These natural filters acts as low-pass filters, which are placed at the physical boundaries of the subsystems. Examples of natural filtering for the AMEPS model are shown in Table 3-8.

Table 3-8 Example of natural filtering

Fast to slow transition location	*Data transferred*	*Natural filtering aspect*
Electrical generator (fast) to internal combustion engine (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

However, it is recognised that where disturbances close to a naturally-filtered boundary are introduced, conflicts may arise between the averaging behaviour 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 synchronising the fast and slow sides of the boundary more frequently, at the cost of poorer computational efficiency.

3.6.3 Error propagation assessment

Quantifying the propagated error as a result of latching is challenging 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. In order to provide such quantification, the multi-rate results have to be compared against the single-rate results. In addition common simulation errors, which are present in any ODE simulation, needs to be quantified. Generally the common simulation error E in numerical analysis is the difference between the analytical y (exact or true) solution and the approximate $\hat{y}$ solution, which can be expressed as [Chapra06]:

$$\begin{aligned} y &= \hat{y} + E \\ \hat{y} &= y - E \end{aligned} \tag{3.15}$$

In general E consists of truncation error E_{tr} and a round-off error E_{ro} and is defined by Chapra and Canale [Chapra06] as follows:

- *"Truncation, or discretisation, errors caused by the nature of the techniques employed to approximate y"*
- *"Round-off errors caused by the limited numbers of significant digits that can be retained by a computer".*

More background information on the truncation error can be found in Appendix A.2. As for E_{tr}, this composes of two parts; the LTE and the propagated truncation error (PTE). The LTE is the truncation error after one step whereas the PTE is the accumulated effect of all LTEs [Cheney94]. The sum of these two parts is referred to as the total or global truncation error (GTE). Therefore the following is true as well: GTE = E_{tr}.

One way to reduce E_{ro} is to increase the number of significant numbers. It turns out that there is a trade-off between minimising the E_{tr} and E_{ro}. Reducing the time-step can reduce E_{tr} but increase E_{ro}. This is due to the fact that a reduction in time-step could lead to subtractive cancellation and an increase in the number of computations, which will in turn increase the E_{ro} [Chapra06]. However, as stated by Chapra and Canale [Chapra06], most computers have sufficient significant figures for E_{ro} not to be predominating. Therefore, generally E_{ro} can be neglected hence $E = E_{tr}$.

Multi-rate errors E_{multi} may need to be added to E_{tr} if a multi-rate simulation method is used. Hence (3.15) can be rewritten as (3.16) where $E=E_{tr}+E_{multi}$.

$$y = \hat{y} + E_{tr} + E_{multi} \tag{3.16}$$

Generally it can be stated that an error in a single step may hardly affect the solution. However, after hundred thousands of steps, the accumulated error may be significant as an error is carried forward in all succeeding steps. In some cases an error may be magnified in succeeding steps; this depends on the numerical method and the differential equations involved [Cheney94].

Sørensen *et al.* [Sørensen14] conducted some quantitative investigations into the errors of multi-rate simulations. For example, in order to determine the “true” solution, a single-rate simulation was simulated first with a 1ms time-step. Next a simulation was run with a 2ms time-step. By comparing these two simulation results, it was concluded that the error had converged and that therefore the true solution was obtained. Although this approach by Sørensen *et al.* gives a good approximation of the “true” solution, this may not always be a practical method as this requires to run the model in single-rate a number of times (with different time steps) until the model converges.

This is in particular true for complex multi-domain systems, which has a significant computational burden and are therefore difficult to run. In order to assess the multi-rate error, Sørensen *et al.* compared the results of a multi-rate simulation against the obtained true solution.

The equations in this section provide a conceptual idea of the errors. However, deriving each term in the equations is far from straightforward. The bullet points provide insights why it is not a straightforward task:

- The AMEPS model or any complex integrated-model cannot be solved analytically due to its complexity. Therefore, the true solution cannot be constructed directly. It can only be approximated. For example by the true solution method proposed by Sørensen *et al.* [Sørensen14], although this may not be practical for large complex systems.
- Obtaining the single-rate solution for comparison reasons with the multi-rate is difficult due to excessive computational burden. For example, in the AMEPS model a single-rate simulation takes approximately 15 times longer to run than a multi-rate simulation.
- Estimating the GTE is challenging as there are several feedback and feedforward loops in complex integrated-model. In addition the GTE will be different for the single-rate and multi-rate simulation due to for example the different time-steps used.
- Without a good estimation of the true solution, the single-rate solution and the GTE, quantifying the propagated multi-rate error is not possible.

Although the propagated multi-rate error has been described conceptually in this thesis and was published in several publications, more in depth mathematical work is needed to develop alternative means for quantification. This mathematical analysis is outside the scope of this thesis and will therefore be proposed as recommended future work.

3.7 Chapter summary

An overview was presented of approaches and techniques related to multi-domain modelling and simulation of physical systems. As a solution to improve the computational efficiency, the concept of multi-rate simulation was introduced. One main drawback of this technique is the potential latching, which may cause simulation errors. These errors were conceptually discussed. The AMEPS model was introduced as a typical example of an IFEP vessel. Where applicable the modelling and simulation techniques for multi-domain modelling were applied to the AMEPS model. It was demonstrated that the multi-rate simulation improved the simulation speed by a factor 10-15. In terms of validation, the propulsion motor was for example field validated whereas the entire integrated-model was face validated.

Chapter 4 Holistic System Behaviour of IFEP

4.1 Chapter overview

Several techniques discussed in the previous chapter, were applied to the AMEPS model. This chapter reports on the development of the AMEPS model and demonstrates how this model can be used in de-risking the design and in-service of IFEP systems. The results and discussions on the research conducted in this chapter have been published in a number of papers including Norman *et al.* [Norman06a and Norman06b] and Schuddebeurs *et al*. [Schuddebeurs07b, Schuddebeurs08a, Schuddebeurs08b, Schuddebeurs08c and Schuddebeurs10].

4.2 Introduction

With the IFEP concept increasingly adopted by the commercial and military shipping industry, there is a need to shift the paradigm in the way marine power systems are modelled. Due to coupling of virtually all loads and prime movers electrically, disturbances anywhere in the system can provoke primary and higher order responses in any of the subsystems connected [e.g. Norman06a and Schuddebeurs10]. These responses could lead to saturation behaviour of controllers, which eventually may lead to dangerous situations such as too slow response of propulsion motors during DP operation. However, in order to capture and investigate these responses an integrated-model is required, which contains high fidelity submodels and allows for acausal signal flows. Once such a model is developed, the model can be subjected to disturbances, which may occur during the operational lifetime of the ship. For example sudden loss of the propulsion load can be investigated with an integrated model – disturbance may have a significant impact on the rest of the systems and protection and control strategies may need to be developed to mitigate the consequences of such an event.

4.3 Integrated-model development

As opposed to the electrical network model the gas turbine, electric drive, propulsion motor and propeller submodels will not be discussed in great detail as these models were developed by the Universities of Cranfield and Manchester respectively.

4.3.1 Gas turbine model

4.3.1.1 Generic gas turbine modelling

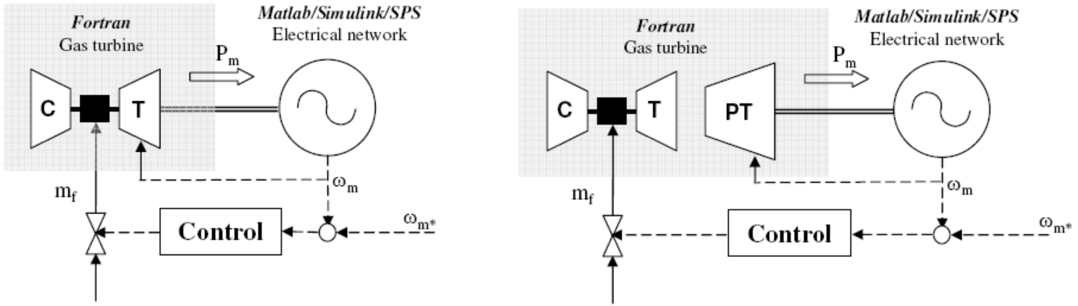
Different papers on gas turbine modelling have been published of which key papers for this thesis are listed here. Yee *et al*. [Yee08] compared various gas turbine models available for system stability studies, which include physical models and the IEEE model. The physical models utilise the conservation laws of mass, power and energy to govern the thermodynamic behaviour in the Brayton cycle. The IEEE model consists of two parts where one part represents the control loops and one part represents the thermodynamic behaviour of the gas turbine.

Centeno *et al*. [Centeno05] presented a turbine model typically used in stability studies, which consists of three different control loops: load-frequency control, temperature control and acceleration control. During normal operating conditions only the load-frequency control is active. The temperature control and acceleration control becomes active during abnormal operating conditions such as exhaust gas temperature exceeding the limit value.

Mody [Mody09] conducted a literature review on gas turbine modelling. It is mentioned in his report that the most accurate gas turbine model would be able to govern all three transients. However, this would make such a model highly complex. Most present transient models will include the shaft dynamics due to its importance and the ease of applying modelling and simulation techniques. The capability to capturing thermal transients is not always included in the model. This is because the theoretical analysis of heat transfer between the gas and metal during a change in engine operating conditions is difficult.

4.3.1.2 Gas turbine model used in AMEPS model

The gas turbine model used in the AMEPS model is a thermodynamic representation, which in this case defines the performance of the engine. Both a single-spool and a two-spool gas turbine were modelled although the latter is more common. Such an approach facilitates investigations into the comparative behaviour of these designs in terms of for example thermal efficiency and transient response. The modelling interfaces between these gas turbine models and the electrical network model is illustrated in Figure 4-1.



a) Single-spool

b) Two-spool

C	Compressor
T	Turbine
PT	Power turbine
m_f	Fuel flow
P_m	Mechanical power
ϖ_m	Measured generator speed
ω_{m*}	Desired generator speed

Figure 4-1 Gas turbine/generator interfaces

The only output from the FORTRAN gas turbine model that acts as an input to the SPS electrical model is the mechanical power P_m, which drives the electrical generator. The difference between P_m and the electrical power P_e is defined as ΔP, which determines the acceleration or de-acceleration of the electrical generator and hence the network frequency. In fact ω_m changes proportional to ΔP and inversely proportional to the angular moment of inertia M.

$$\omega_m = \frac{1}{M}\int \Delta P dt \qquad (4.1)$$

In steady state operation P_m and P_e are in equilibrium, which means that ΔP is equal to zero and ω_m is constant. However, due to changes in for example load demand ω_m increases or decreases. The difference between ω_m and ω_m* is used in a negative feedback loop that controls m_f, which is one of the inputs to the gas turbine model. In addition ω_m is an input to the PT for the two-spool model and to the turbine for the single-spool model.

It is common practice to model a gas turbine with a ω_m output instead of P_m, where the speed differential equation (4.1) is solved in the gas turbine model. This would have caused an additional challenge, as the generators normally require P_m as an input. However, by moving the speed differential equation from the gas turbine model to the generator model, no additional matching blocks were required.

4.3.1.3 Speed controller model used in AMEPS model

Information on the system frequency and load demand is received by the primary controller; the speed/load controller – also known as speed governor[12]. When only one generation-unit is connected to the system, the governor can be of the isochronous type. This means that the governor tries to keep the frequency constant at a predefined value ω_m*. Any deviation from ω_m* results in a control action of the governor, which in turn regulates the m_f to the prime mover. For example an increase in load causes the system frequency ω_m to drop. As a result the governor increases m_f in order to supply more power to the generator until equilibrium is reached between ω_m and ω_m*.

If two or more generation-units are connected to a system, isochronous governors are not used as this would require all generators to have exactly the same speed setting. If these generators have different speed settings, they would fight each other in order to control the systems frequency

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[12] For consistency, the terminology "governor" will be used for the remainder of this thesis.

[Kundur93]. For such systems where more than two generation-units are required to run in parallel, governors with a droop-characteristic can be used, which provides a stable load share between the generation-units. As a droop-characteristic moves the frequency away from its set point if the generator load is changing, an additional control is required that moves the droop line up or down in order to maintain the desired frequency. This type of control is referred to as secondary control.

4.3.2 Propeller and vessel model

4.3.2.1 Propeller model used in AMEPS model

The propeller load is commonly modelled as follows [e.g. Apsley09, GonzalezVillaseñor06b and KleinWoud03]. From non-dimensional thrust (K_T) and torque (K_Q) coefficients the propeller thrust (T) and torque (Q) can be calculated using the following equations.

$$T = \rho n^2 D^4 K_T \tag{4.2}$$

$$Q = \rho n^2 D^5 K_Q \tag{4.3}$$

where ρ [kg/m^3] is the water density, n [rev/s] is the propeller speed and D [m] is the propeller diameter. The thrust and torque coefficients are a function of the propeller geometry and the non-dimensional advance ratio J. This J is calculated as the ratio of the ship advance speed V_A [m/s] and the propeller speed.

$$J = \frac{V_A}{nD} \tag{4.4}$$

The advance speed gives the speed of the water at the propeller, which is less than the ship speed V_S due to the wake. V_S can be expressed as:

$$V_A = V_S(1-w) \tag{4.5}$$

where w is the wake fraction, which is a ship design parameter. K_T and K_Q are a function of J, which is normally characterized in an openwater[13] propeller diagram such as the Wageningen [Kupier92] series. This openwater diagram does not include the interaction with the hull. Normally, the openwater diagram only holds for positive values of J (positive V_A and nD). For negative V_A and nD, modified K_T and K_Q are used as function of the advance angle β, which is the angle of the resultant of the propeller velocity and advanced speed [e.g. Apsley09, GonzalezVillaseñor06b and KleinWoud03].

$$\beta = \tan^{-1}\left(\frac{V_A}{0.7\pi nD}\right) \tag{4.6}$$

4.3.2.2 Vessel model used in AMEPS model

In order to convert the propeller thrust into the vessel speed, a model has been used, which is based on the following equation. (4.7) calculates the ship speed V_S as a function of the propeller thrust T, the ship resistance R_f and the ship's point inertial mass m.

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[13] An open-water test is used to assess the performance of a propeller. In this test, the propeller is operated in an open tank or tunnel where the front of the propeller experiences uniformly distributed water flow.

$$V_S = \frac{1}{m}\int (T - R_f)\,dt \tag{4.7}$$

The ship resistance R_f to motion was modelled with the assumption that the frictional component is dominant and the pressure resistance can be neglected [GonzalezVillaseñor06b]. In (4.8) R_f is a function of the friction coefficient C_f, the water density ρ, the wetted surface of the ship S_w and the ship speed.

$$R_f = \frac{1}{2} C_f \rho S_w V_S^2 \tag{4.8}$$

4.3.3 Electrical distribution model

4.3.3.1 General methods

Qi [Qi04] presented an overview of power system modelling and simulation approaches. Essentially, modelling and simulation of power systems can be divided into two main categories: namely the nodal admittance based circuit simulation method and the Differential Algebraic Equation (DAE) solver based method. The former method in essence represents a power system at each time-step as an electric circuit of mixed constant impedance and voltage source. This method is for example implemented in the EMTP/ATP /Alternative Transient Program). The latter method, as for example implemented in SPS, relies on implicit or explicit numerical integration methods to solve the ODEs and DAEs. [Qi04, Yang07]. The AMEPS electrical network model relies on ODE solvers.

4.3.3.2 Generic power converter modelling

The literature on modelling and simulation of power converters is diverse and extensive of which some are discussed next. Gole *et al.* [Gole97] provides a number of guidelines for modelling power converter in electric power engineering systems. Two basic solution methods are considered in [Gole97], which includes the frequency domain and time domain method where the former is based on discrete frequency intervals and the latter on discrete time-steps (Δf and Δt respectively). As for the frequency domain method a circuit solution is found for each individual frequency, truncation errors are not accumulated. Therefore this method is more robust than the time domain method where integration methods are applied to discrete time-steps. For time domain simulations, the solution stability and accuracy are closely related to the size of the time-step. It has been reported by [Gole97] that the time domain method has great advantages over the frequency method in terms of handling system dynamics, power converter interfaces and transients. A popular software tool for power converters and digital circuits is SPICE.

Norman *et al.* [Norman08] discussed the difficulty of modelling power converters computationally efficiently. Particularly power converter dense systems require a careful choice of simulation time-step in order to maintain numerical stability and at the same time minimise the simulation execution time. In [Norman08 and Qi11] a number of approaches to simplify power converter models were discussed. These include voltage and current source representation, functional modelling and averaged switch modelling. The first two methods utilise controlled voltage and current sources, which use the switching pulses from the high-fidelity model. This approach result in a much improved computational efficiency as the output responses of the models represent the power converter accurately without actually modelling the switching of the power converter. However, the voltage and current source representation method only permits a data flow from the DC to the AC side of the power converter model so that interactions between the DC and AC side cannot be captured. The functional modelling however, allows for capturing some interactions as some additional sources and measurement functions are included.

4.3.3.3 Power converter model used in AMEPS model

In terms of time-step and simulation execution time, the limiting component in the electric drive model is the power converter. Tests showed that the optimum location for the interface between the electrical network model and the electric drive model is at the DC link, as shown in Figure 4-2, where the current matching takes place in the DC link capacitor.

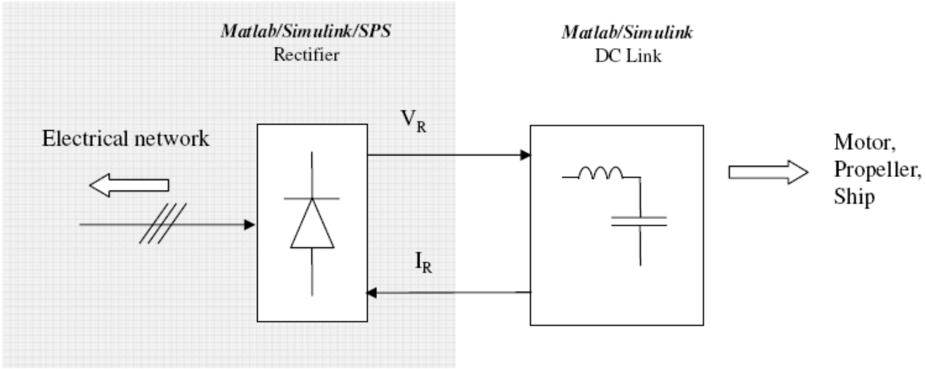
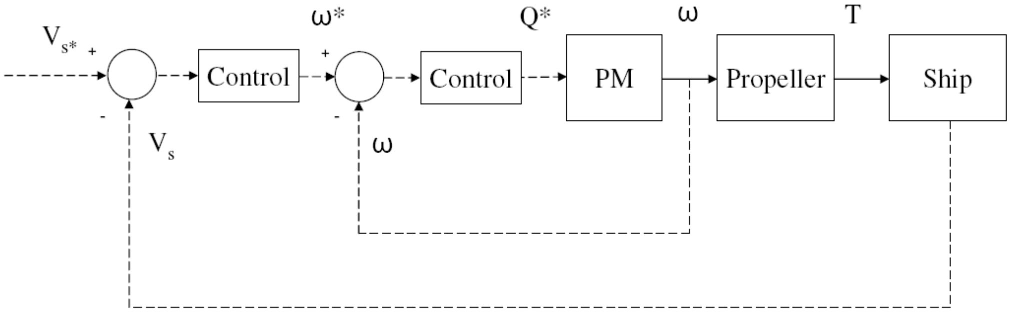


Figure 4-2 Electrical network/electric drive interface

The bidirectional data flow consists of the rectifier voltage V_R from the rectifier and the rectifier current I_R from the DC-Link. As V_R depends on I_R, algebraic loops are formed, which are difficult to solve. However, by modelling the DC link as a state-space model, I_R depends only on previous values of V_R so the formation of algebraic loops is avoided.

The control system of the electric drive consists of a cascade control loop as shown in Figure 4-3. The electric propulsion motor is modelled as a 15-phase induction motor with closed-loop field oriented control as used in the Type 45 Destroyer.



V_S	Measured ship speed
V_S*	Desired ship speed
ω	Measuered rotational motor speed
$\omega*$	Desired rotational motor speed
$Q*$	Desired motor torque
T	Propeller thrust

Figure 4-3 Ship speed control loop

4.3.3.4 Static load models used in AMEPS model

Apart from the dynamic load on the MV bus, i.e. the electric propulsion motor, a number of static power loads were added to both the MV and LV busbars to represent for example auxiliary loads. These static loads were modelled as a constant impedance load as this is common practice in power system studies [Radan08]. A power factor (*pf*) of 0.85 was used in this case. (4.9) shows the calculation for the constant impedance loads [Kundur93] where subscript *0* identifies the initial condition of the variable and *V* the bus voltage.

$$\begin{aligned} P &= P_0 \left(\overline{V}\right)^2 \\ Q &= Q_0 \left(\overline{V}\right)^2 \end{aligned} \tag{4.9}$$

4.4 Case study – AMEPS model

The AMEPS model was subjected to extreme event scenarios, which may disturb the power system significantly in order to obtain a holistic system appreciation under severe operating conditions. These scenarios are:

- *Significant Load step:* A sudden and instantaneous loss of the propulsion load, which may be a result of a malfunctioning electric drive, changes the power balance instantaneously. As a result non-acceptable large frequency swings may occur.
- *Cyclic loading:* A cyclic load added to the steady state propulsion load, which may be due to heavy sea state. As a result the power balance changes periodically and non-acceptable large frequency swings may occur.

Based on these types of case studies more adequate control strategies can be developed, which tailors to a more optimized overall control strategy. This case study has also been reported in [Schuddebeurs07b, Schuddebeurs08a, Schuddebeurs08b, Schuddebeurs08c and Schuddebeurs10].

4.4.1 Significant load step scenario

In this scenario a severe event is simulated, as indicated by the AMEPS industrial partners, in which the power drawn by the propulsion motor instantaneously drops from the nominal power at cruising speed to zero. This could be due to an internal power converter or motor fault (for example due a malfunctioning cooling system), a sustained overload or high shock load in the mechanical system. This scenario was modelled by setting the demanded motor torque to zero after some time into the simulation. As a result the power delivered to the propeller drops to zero within a few milliseconds, after which the ship will coast to a halt and the propeller will freewheel. However, the power converter and motor remain energised and continue to draw a small amount of power required by the motor field. In addition a relatively small amount of power is drawn by a parallel resistor in the rectifier that is required to maintain the numerical stability of the simulations. This implementation was chosen since it gave a rapid reduction of load in a manner that could be readily simulated on the platform used.

The first part of this section summarises the simulation results of the AMEPS model in which a two-spool gas turbine was used. The second part summarises the simulation results in which the behaviour of a two-spool gas turbine was compared against that of a single-spool.

4.4.1.1 Results two-spool gas turbine

Figure 4-4 - Figure 4-8 show the simulation results for this event, which was initiated 0.5s after the start of the simulation. Figure 4-4 shows a graph of the desired (blue dotted line) and actual (green solid line) 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.

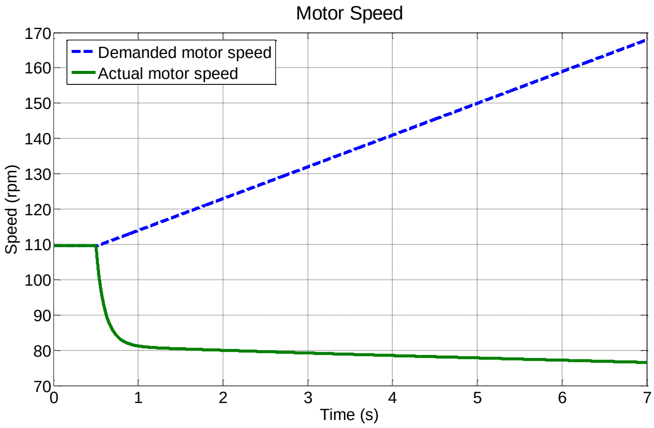


Figure 4-4 Propulsion motor speed; load step

The three-phase MV voltage and current traces (measured at the terminals of the generators) are shown in Figure 4-5. Note that these plots are shown over a much shorter time frame than the other parameters presented in order to highlight the waveform distortion 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.

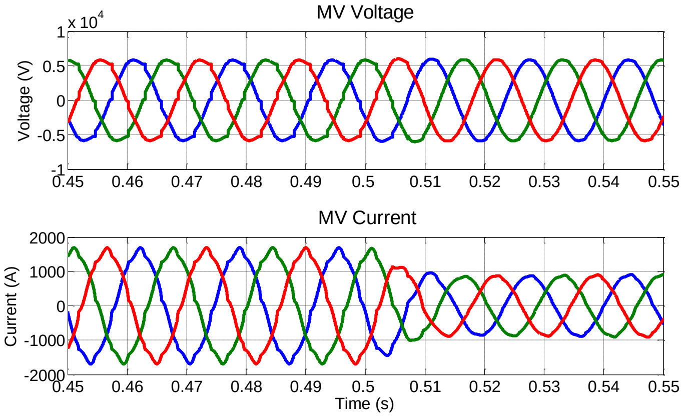


Figure 4-5 MV voltage and generator current; load step

Figure 4-6 shows the demanded (blue dotted line) and actual (green solid line) gas turbine fuel flow. Immediately after the sudden and instantaneous 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 m_f demand to the minimum level. However, in order to prevent damage to the gas turbine, the rate of change for the actual m_f is limited by internal controllers. This limiting action of the fuel flow controller, sometimes referred to as saturation, is evident in the plot of actual fuel flow in Figure 4-6. This in turn causes the power output of the gas turbine (Figure 4-7) 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 4-8).

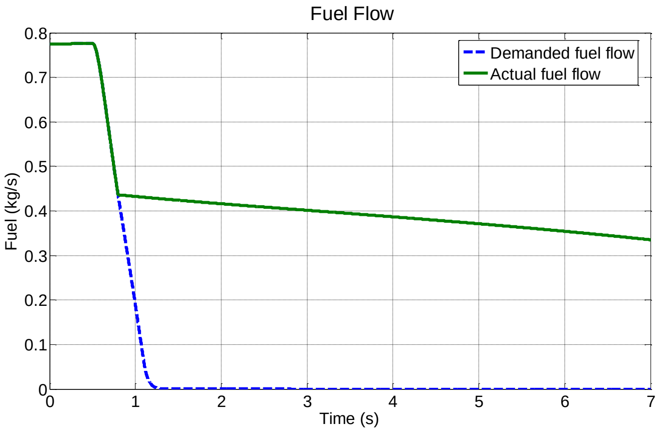


Figure 4-6 Gas turbine fuel flow; load step

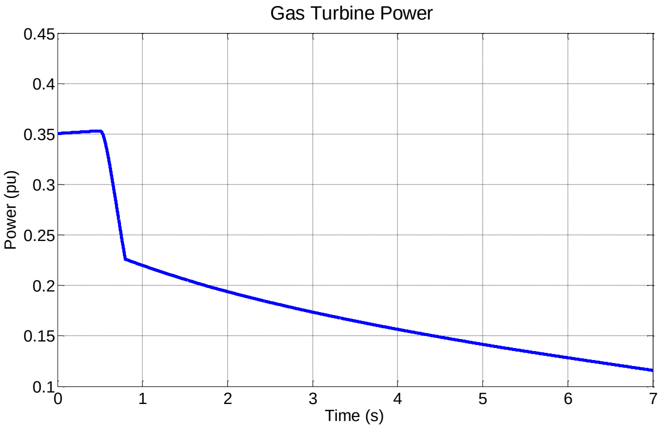


Figure 4-7 Gas turbine power; load step

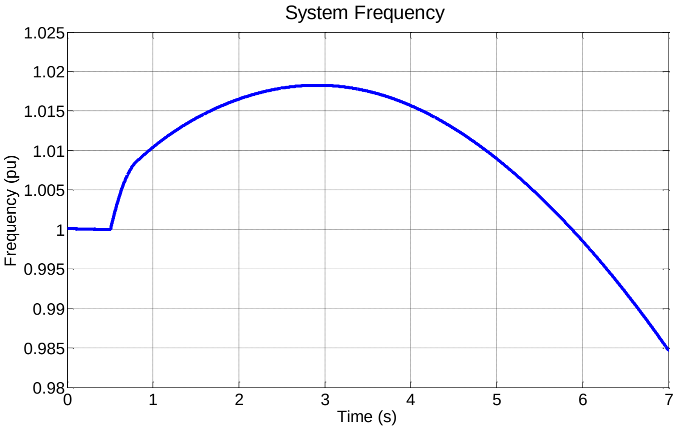


Figure 4-8 System frequency; load step

4.4.1.2 Results comparison two-spool and single–spool gas turbine

Figure 4-9 - Figure 4-12 show the comparison between the two-spool and single-spool gas turbine behaviour. As opposed to the single-spool gas turbine, in the two-spool gas turbine a lag to the response time of the power turbine is added due to the presence of a separate gas generator.

Since the two-spool gas turbine power decreases slowly, the system frequency increases due to the excess of the supply power relative to the demanded power. This behaviour continues until approximately t=5s, see Figure 4-9 and Figure 4-10, where at that point the gas turbine power becomes less than the demanded power and hence the system frequency begins to decrease. After the loss-of-propulsion load, the demanded power by the electrical system is about 4MW lower than the gas turbine power. Therefore the governor control system needs to reduce the fuel flow m_f to the gas turbine to zero till the supply power matches the demanded power. However, the rate of change of the fuel rack is limited in order to protect the gas turbine. As a consequence the decrease of gas turbine mechanical output is slower than desired. Figure 4-9 and Figure 4-10 show that the single-spool gas turbine almost responds instantaneously to the sudden loss-of-load. Since the power supplied by the gas turbine matches the demanded power within 0.5s after the loss-of-propulsion load, the system frequency remains relatively constant.

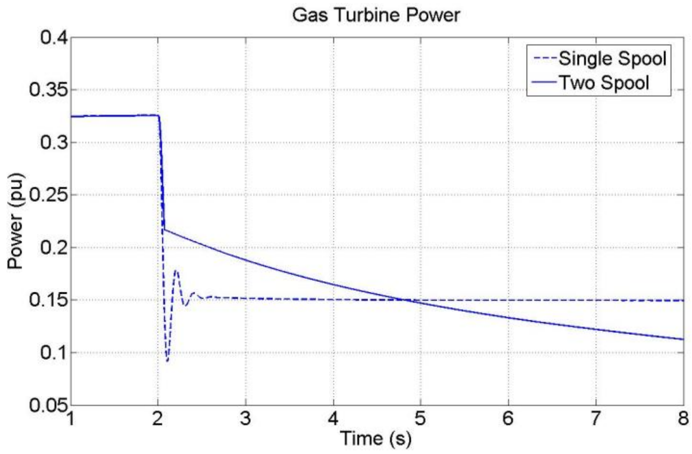


Figure 4-9 Gas turbine power single-spool and 2-spool; load step

The corresponding system frequency for both types of gas turbine is illustrated in Figure 4-10 where the horizontal lines represent the frequency limits as defined by the classification society Det Norske Veritas [DNV01]. According to DNV, the maximum allowable variation in steady state frequency is between 95% and 105% of the fundamental frequency although a variation of 10% is permitted during load changes. Based on the simulation results of the two-spool gas turbine, it can be concluded that the DNV transient frequency limits were exceeded during the loss-of-load event.

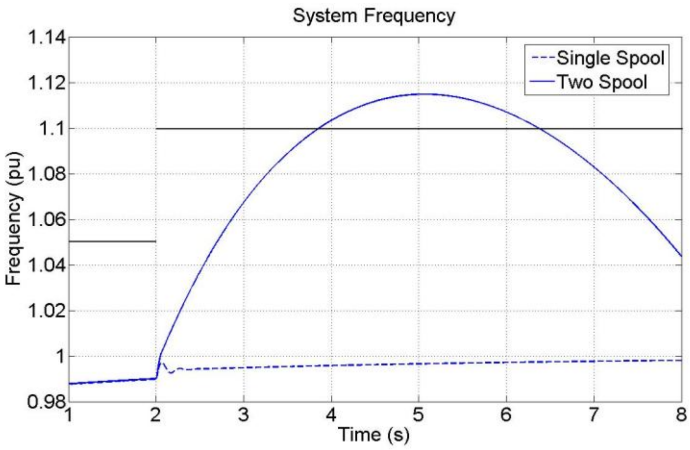


Figure 4-10 System frequency single-spool and 2-spool; load step

The fuel flow response for both the single-spool and two-spool are presented in Figure 4-11. In case of the two-spool gas turbine the blue solid and grey dotted lines represent the actual and required fuel flow respectively. This clearly demonstrates that the actual fuel flow is significant different from the required fuel flow. The blue dashed line represents both the actual and required fuel flow of the single-spool gas turbine as there is no saturation in this case.

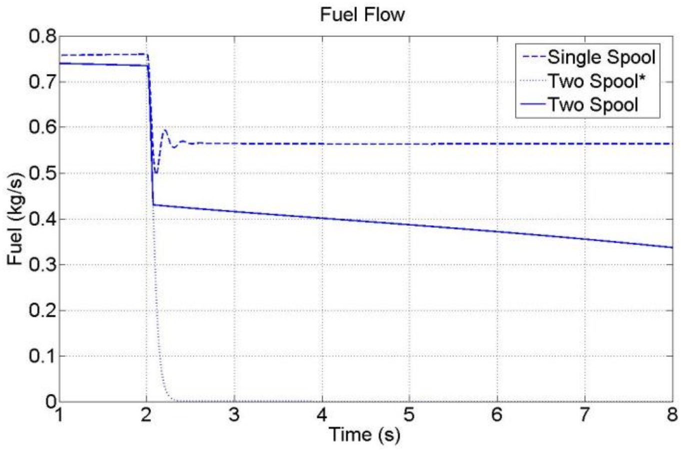


Figure 4-11 Fuel flow single-spool and 2-spool; load step

Figure 4-12 illustrates the Exhaust Gas Temperature (EGT) of both the single-spool and two-spool gas turbine, which is represented by the dashed line and solid line respectively. As the EGT is an indication of its overall efficiency, the two-spool gas turbine in this case is more efficient than the single-spool gas turbine because of the higher temperatures seen at its exhaust. Although very high values of EGT are desired, there are limitations due to the mechanical integrity of the components utilised.

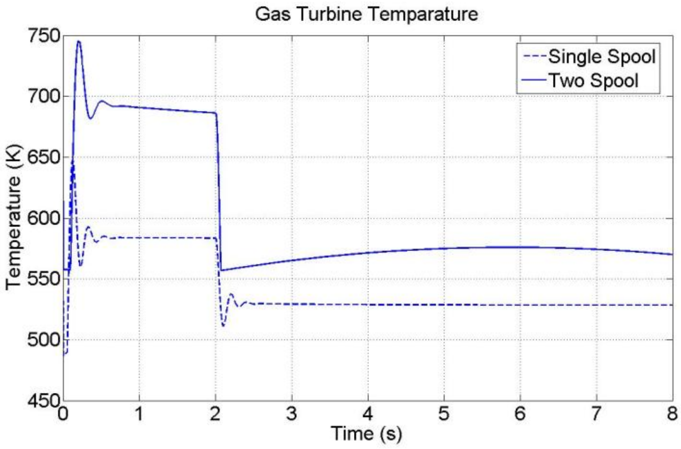


Figure 4-12 Gas turbine temperature single-spool and 2-spool; load step

4.4.1.3 Discussion of Results

This case study is an excellent illustration of the potential interactions that can take place within IFEP power systems. It clearly illustrates that events in one part of the system can have an effect on, and provokes responses from, other components. In this case non-linear effects, i.e. saturation, in the two spool gas turbine control caused exaggerated swings in the network frequency and a particularly poor system response to the original perturbation. Degraded power quality is thus being supplied to the rest of the loads connected to the network. This may also have further undesirable consequences, such as nuisance tripping of sensitive loads.

An improved control scheme for the gas turbine can 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.

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.

4.4.2 Cyclic loading scenario

This scenario focuses on a cyclic loading profile experienced by the propeller and hence by the electric propulsion motor. These cyclic loading on the propeller can be the result of the vessel sailing through heavy seas, whereby the stern of the vessel may periodically come (partially) out of the water. In this case study, the cyclic load profile on the propeller is assumed to be a pure sinusoid with a frequency and amplitude 0.1Hz and 10% rated thrust respectively. The propeller loading profile is in line with the range of realistic values given in [Stewart05]. This cyclic loading profile was started 0,5 seconds after the start of the simulation.

4.4.2.1 Results

The effect of the cyclic loading on the propeller can be observed in Figure 4-13 - Figure 4-17. In contrast to the previous scenario, there is no control saturation present within the gas turbine in this mode of operation. Therefore the actual fuel flow is the same as the demanded fuel flow as illustrated in

Figure 4-15. 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.

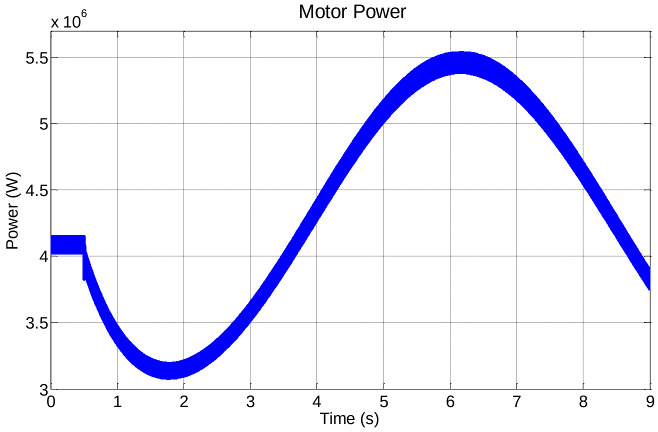


Figure 4-13 Motor power; cyclic loading

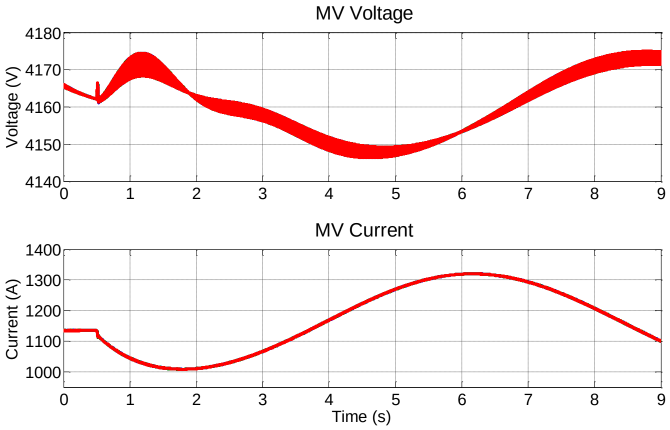


Figure 4-14 Voltages and currents; cyclic loading

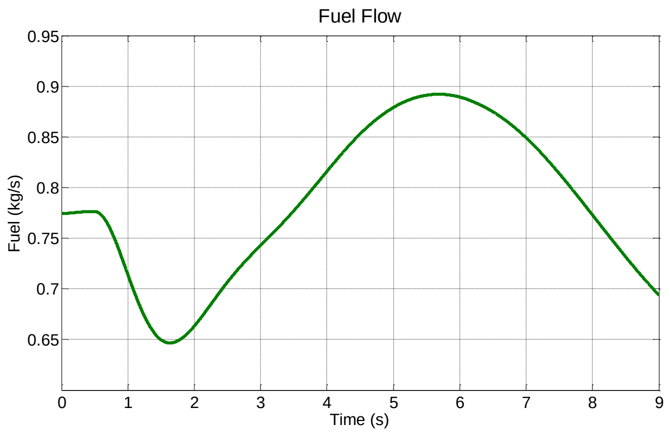


Figure 4-15 Fuel flow; cyclic loading

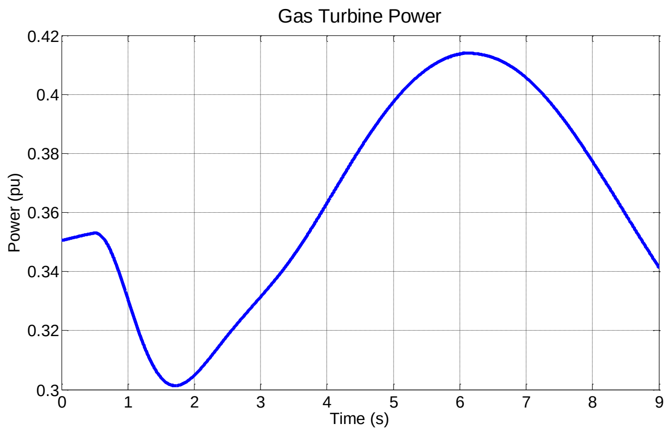


Figure 4-16 Gas turbine power; cyclic loading

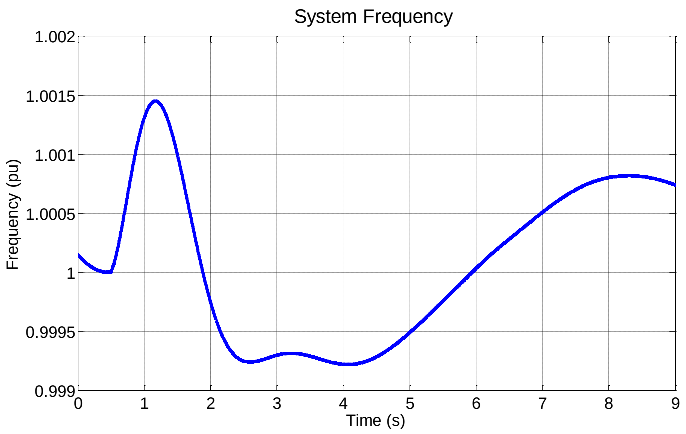


Figure 4-17 System frequency; cyclic loading

4.4.2.2 Discussion of results

Subjecting the model to a wave disturbance has demonstrated that the system frequency stay well within the limits. Although the gas turbine governor system does not show any saturation, frequent fluctuations as experienced in this scenario may lead to accelerated aging of components. While this scenario with a single wave frequency provide good results, in reality propulsion systems are subjected to sea waves, which are composed of a range of frequencies [Stewart05]. The response of the propulsion system to these different disturbance frequencies will therefore be different and this may result in a far greater impact on the prime mover operation and network frequency than presented here [Elders08].

4.5 Chapter summary

In this chapter the application of modelling and simulation techniques from the previous chapter to an integrated-model of a typical IFEP vessel, the AMEPS model, was presented. It was demonstrated that high fidelity models from the thermal, mechanical and electrical domain can be integrated in a single model in such a way that bi-directional flows at the interfaces are captured adequately. In one case study the propeller was subjected to a disturbance and an unexpected saturation response from the gas turbine governor was observed. This demonstrates that the model can be used to capture not only the primary responses to a disturbance but also the higher order responses.

Chapter 5 IFEP Power System Architecture Philosophies

5.1 Chapter overview

This chapter provides a comparison study between several present and future- proposed IFEP power system architecture philosophies including a radial, ring and hybrid AC/DC architecture. In particular, the impact of large disturbances, such as short circuits, on power availability and hence vessel survivability has been investigated. Parts of the work described in this chapter have been presented in Booth *et al.* [Booth08] and Schuddebeurs *et al.* [Schuddebeurs07a].

5.2 Introduction

Although numerous IFEP power system architecture philosophies exist or have been proposed, so far little discussion has been conducted with respect to the impact of different architectures on power availability and vessel survivability. Investigating this impact has become increasingly important as more (critical) loads depend on a reliable power system. In case of naval vessels, failure of the power system may jeopardise the chances of survival (both with respect to vessel and crew) during battle situations as ship mobility and enemy detection systems increasingly depend on electrical power. Also in case of non-military vessels, failure of the power system may jeopardise the chances of survival. For example vessels with DP systems, such as OSV, may run into dangerous situations if the power system fails during sea operations.

5.3 Survivability

The terminology *vessel survivability* is commonly used with respect to naval architectural issues such as hull integrity after damage to the hull (for example due to collision or battle conditions). However, with the introduction of more advanced marine power system concepts, including IFEP, vessel survivability does no longer limit itself to naval architectural issues. Marine power systems have become increasingly important for vessel survivability as for example with the IFEP concept, power systems also supply electrical power to mission-critical systems such as electric propulsion motors and battle systems (e.g. weaponry and radar systems) [Zgliczynski06].

In 2003 Gyparis *et al.* [Gyparis03] concluded that the quantification of survivability, in terms of an absolute measure, is difficult if not infeasible. It was therefore suggested that a relative comparison between different designs/architectures would be more appropriate [Gyparis03]. However, in 2011 Chalfant and Chryssostomidis [Chalfant11] presented a paper on a survivability metric, which measures two distinct issues. The first metric determines, whilst proceeding in priority order, the maximum value of all loads that still can be supplied. This metric (overall survivability score) indicates an overall ability to provide and distribute power in case of damage. The second metric calculates the highest priority loads that cannot be supplied. This metric (survivability tier score) is an indication of the severity of the impact of lost loads. A max-flow and a min-cost algorithm were adopted to calculate the scores. In addition a blast model was used, based on Monte Carlo methods, to randomly place disturbances throughout the ship. The case study presented in this paper involves the comparison of a ring and a breaker-and-a-half (upgraded ring) IFEP architecture subjected to blast disturbances. It was concluded that the ring architecture is more survivable due to the reduced power converter redundancy in the breaker-and-a-half architecture. Although the survivability method proposed by Chalfant and Chryssostomidis looks very interesting, the max-flow and min-cost algorithm only calculates the optimal electrical flow. Thus power system performance criteria, such as the fault current behaviour, were not considered even though these criteria may play an important role in the survivability of a vessel. In addition the survivability metric methods described in this paper requires a detailed knowledge of the loads in terms of location onboard, criticality and electrical properties. Finally a common IFEP radial architecture was not evaluated in the case study. Because of the discussion above, the work presented in this chapter and published in Schuddebeurs *et al*. [Schuddebeurs07a] is still considered to be of value by the author of this thesis.

Hegner *et al*. [Hegner03] defined naval vessel survivability as the ability of a system (vessel) to avoid a threat (susceptibility), withstand a casualty (vulnerability) and recover from a casualty (recoverability). A casualty, hereafter referred to as disturbance, include a missile hit and other forms of battle damage. Such a disturbance requires the damaged parts of the power system to be rapidly disconnected (by means of adequate power system protection schemes) from the remaining healthy system. In this way healthy parts of the system are no longer directly affected by the effects (e.g. voltage and frequency instability) of a disturbance; they may remain fully operational and therefore contribute to the survivability of the vessel. As parts of the network are isolated, alternative power supply paths to the healthy parts of the system (through adequate system reconfiguration) may need to be considered.

Each of these three aspects of survivability (susceptibility, vulnerability and recoverability) is applicable to IFEP. For example, electrical noise in the electric propulsion drives may be picked up by enemy sensor systems, which will therefore increase the ship's susceptibility. Power system protection and reconfiguration schemes on the other hand are related to the recoverability after a disturbance. Gyparis *et al.* [Gyparis03] defined state components that contribute to the vessel survivability after a disturbance as presented in Figure 5-1a. Each axis of the ABC plot represents one of the following state components: *mobility systems*, *battle systems* and *structural integrity,* which correspond to *A*, *B* and *C* respectively. Maximum survivability state can be achieved if all the state components are at optimum, i.e. no reduced performance of any of the systems. This corresponds to coordinate (1,1,1). Each axis can be broken down into subcomponents. For example axis *A* consists of a *manoeuvrability* and *speed* component, as presented in Figure 5-1b. As both the speed (electric drive and propeller) and manoeuvrability (e.g. either rudder or podded propeller) component requires electrical power, any degradation in the electrical power availability could potentially reduce the mobility systems component and therefore reduce the vessel survivability. Similarly, degradation in the electrical power supply may jeopardise the satisfactory operation of the battle systems.

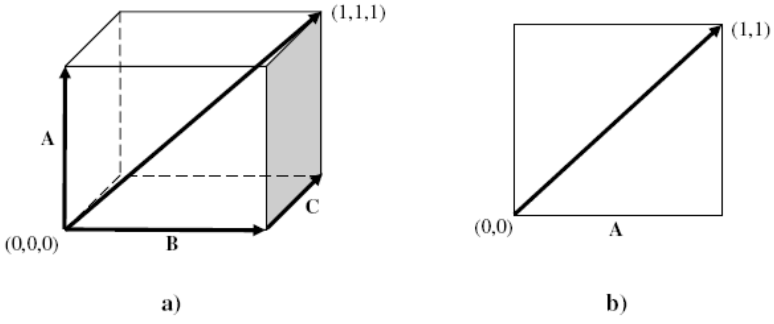


Figure 5-1 Survivability state components

Generally the survivability P_S can be expressed as (5.1) [Gyparis03] where P_R, P_X and P_V are the recoverability, susceptibility and vulnerability respectively.

$$P_S = 1 - (P_X P_V)(1 - P_R) \tag{5.1}$$

Assuming the susceptibility P_X and vulnerability P_V have a maximum and equal value of 1 for all three network architectures, (5.1) can be rewritten as:

$$P_S = 1 - (1 - P_R) \Rightarrow P_S = P_R \tag{5.2}$$

Only the *recoverability* state components associated with *mobility systems* and *battle systems* were considered as these can be applied to the network architectures. *Mobility systems* itself was split up into *manoeuvrability* and *speed*. State component *structural integrity* was not considered as this is related to naval architecture and is therefore outside the scope of this thesis.

5.4 IFEP power system architectures

For this thesis three competing IFEP architectures (an IFEP- radial, an IFEP ring and an IFEP hybrid AC/DC architecture), which could be viewed as the main candidates for marine electrical systems in the future, were compared against each other in order to obtain a relative comparison [Schuddebeurs07a]. The Matlab®/Simulink®/SPS environment was used for this comparison study.

In the previous chapters the development and application of the AMEPS model was discussed. While the high fidelity models of the gas turbine, the electric drives and propellers could be used for the IFEP architecture studies, the computational overhead would increase significantly. However, the response of the various IFEP architectures, in terms of the electrical parameters of interest, is not influenced significantly by the fidelity of the models of the aforementioned system components. Accordingly, abstracted models largely based on transfer-functions and components already available within SimPowerSystems (which have been validated by Mathworks) are considered to be sufficient. Using this approach, the simulation execution times were significantly reduced without compromising the accuracy of the model excessively. Higher fidelity models would need to be used if other aspects of system performance, for example mechanical responses to electrical system faults were of interest.

5.4.1 IFEP-radial architecture

Typical modern electric vessel power system architectures follow the radial design, which consists of a number of generation-units connected to an MV busbar [Husband06]. Usually the MV bus has a (often symmetrical) split design, which can be connected through a tie-breaker. Opening or closing the tie-breakers enables some flexibility in operational modes. Normally for IFEP-radial architectures a form of over-current protection is used for power system protection, which relies on inverse time current relays, also known as Inverse Definite Minimum Time (IDMT). IDMTs protect each feeder in the system in a coordinated fashion whereas the busbars are normally protected by unit-protection. This architecture is well understood and relatively simple and inexpensive. The availability of power may not be as high as other architectures since this IFEP-radial architecture possesses little redundancy.

Figure 5-2 represents a typical IFEP-radial architecture, which was used for the comparison study. Note that only the port or starboard part of the vessel's power system was modelled. The reason is that in normal operation the tie-breakers between port and starboard side of the power system are in the open position. Therefore investigating fault currents and the impact of large load steps in one part (either port or starboard) does not require the other part to be modelled as both parts are disconnected electrically. Diesel engines were considered in this study as these are often used as prime mover in generation-units.

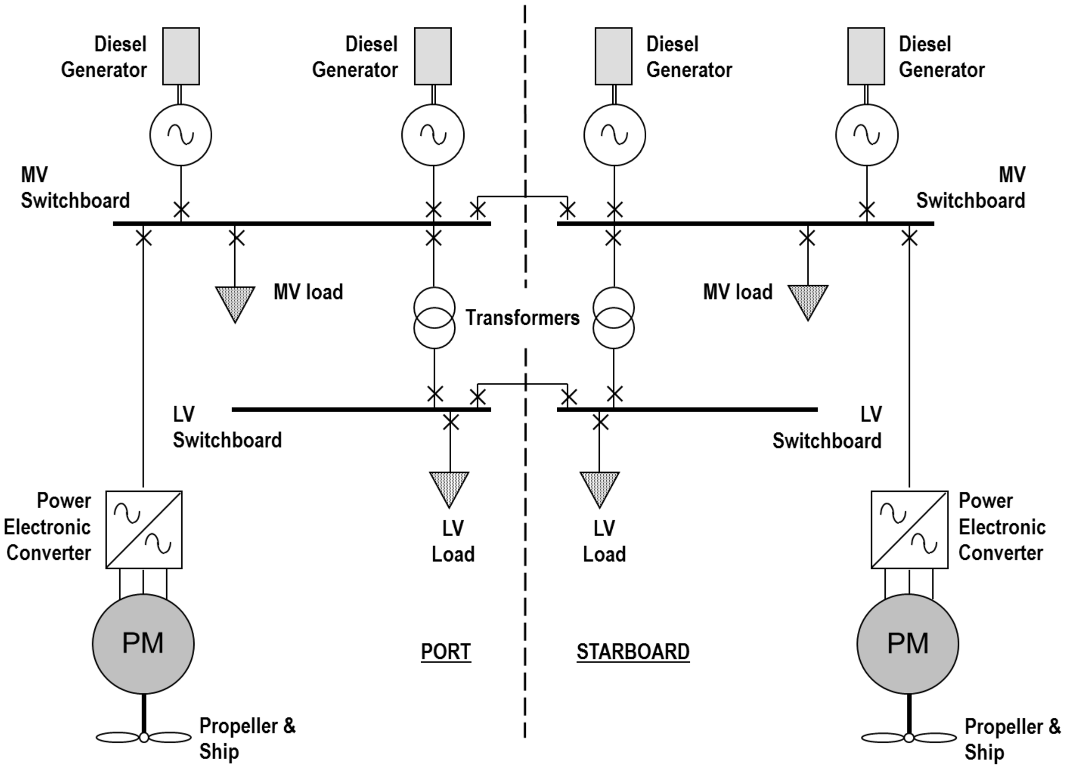


Figure 5-2 Typical IFEP- radial architecture

5.4.2 IFEP-ring architecture

IFEP-ring architectures can be found on vessels such as OSVs, which use DP [Ådanes03]. DP vessels normally operate with open tie-breakers in order to be fault tolerant and hence improve vessel survivability. Therefore a fault in one part of the system would not directly affect the other parts of the network [Ådanes03]. An advantage of the IFEP-ring over the IFEP-radial architecture is that in case of a fault on the MV busbars, alternative paths can be used to maintain power supply to the healthy parts of the system, thus providing improved redundancy. This is achieved by operating the system as a real "ring" with all the tie-breakers closed. This also provides more operational flexibility in for example optimizing the optimal number of generator-units. In addition, load transients are shared amongst multiple generation units [Ådanes03]. Ring architectures possess multiple generation-units; therefore fault currents can be bi-directional depending on the location of the fault. Protecting these systems can be relatively complex and may require the use of directional relays.

Figure 5-3 represents a typical IFEP-ring architecture with all tie-breakers closed. Typically each bus in a ring system would have at least 2 generation-units but for the sake of comparison with the other architectures in this study, 1 generation-unit per bus was modelled.

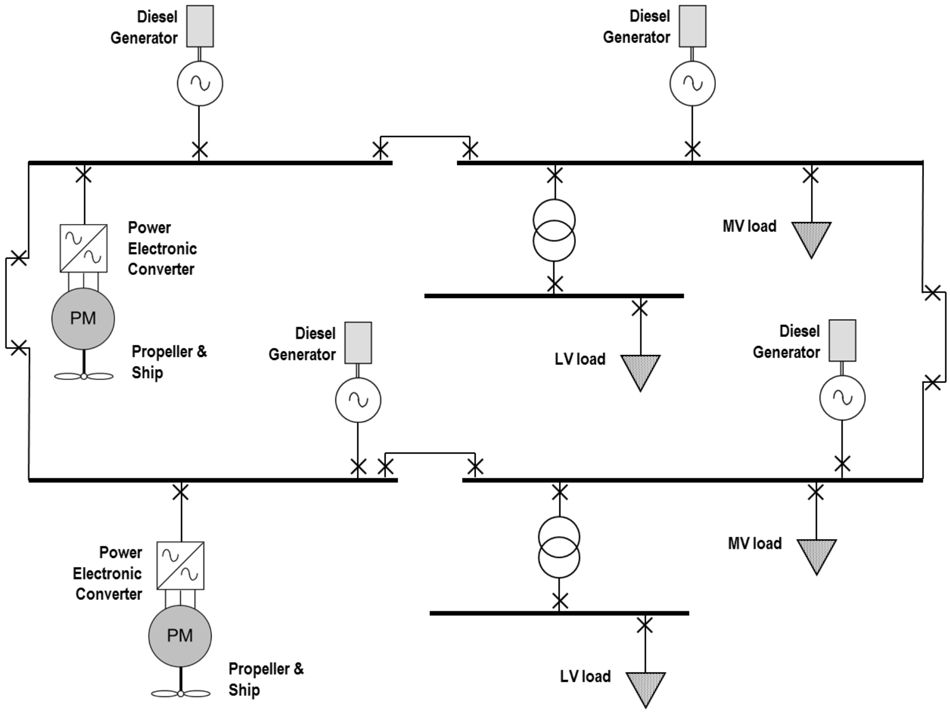


Figure 5-3 Typical IFEP-ring architecture

5.4.3 IFEP-hybrid AC/DC architecture

There has been a debate within the marine shipping community regarding AC versus DC architectures. Similar discussions have taken place in for example the aerospace industry as reported by Fletcher *et al*. [Fletcher08]. DC distribution offers advantages over AC distribution in terms of higher power transfer for similar voltages, fewer conductors, etc. [Newell99]. However, associated disadvantages – including no zero-crossing to aid fault current interruption, increased weight and higher costs – mean that in many cases AC remains the first choice for marine power systems. Nevertheless, in cases where the advantages of DC power distribution systems are vital to achieving the objectives of the vessel, DC power systems are being deployed [Nebb12]. This can be seen in modern applications such as space crafts, fighter aircrafts and some naval vessels. For example most naval mission systems, such as EMALS and battle systems, would require a DC power supply. In addition the power demand for the radar systems for the DDG-1000 is expected to be in the range of 7MW [Zgliczynski06]. The overall philosophy these days is that the question should no longer be “AC or DC” but instead “how much of AC and DC”.

An example of a typical IFEP- hybrid AC/DC architecture is the future US DDG-1000 destroyer. Power is generated at the AC side of the power system at a voltage level of 4160VAC. From the AC side, propulsion motors are supplied and power converters (called PCMs) are used to convert AC into a 1000VDC for the zonal power distribution system [Zgliczynski06].

Figure 5-4 presents a typical IFEP-hybrid AC/DC architecture consisting of an AC distribution system and an LV distribution system. Similar to the IFEP-radial architecture, either the port or starboard part of the power system was modelled. In addition the AC voltage levels are the same as it is for the IFEP-radial and IFEP-ring architecture. However, the LV 440VAC is converted into a 440VDC. The converter is a 6 pulse thyristor, which uses a series LC three-phase filter on the LV AC side to reduce the THD below a threshold value as specified by the DNV. The filter is tuned to present very low impedance to the 5th, 7th, 11th, and 13th harmonics of the fundamental power system frequency.

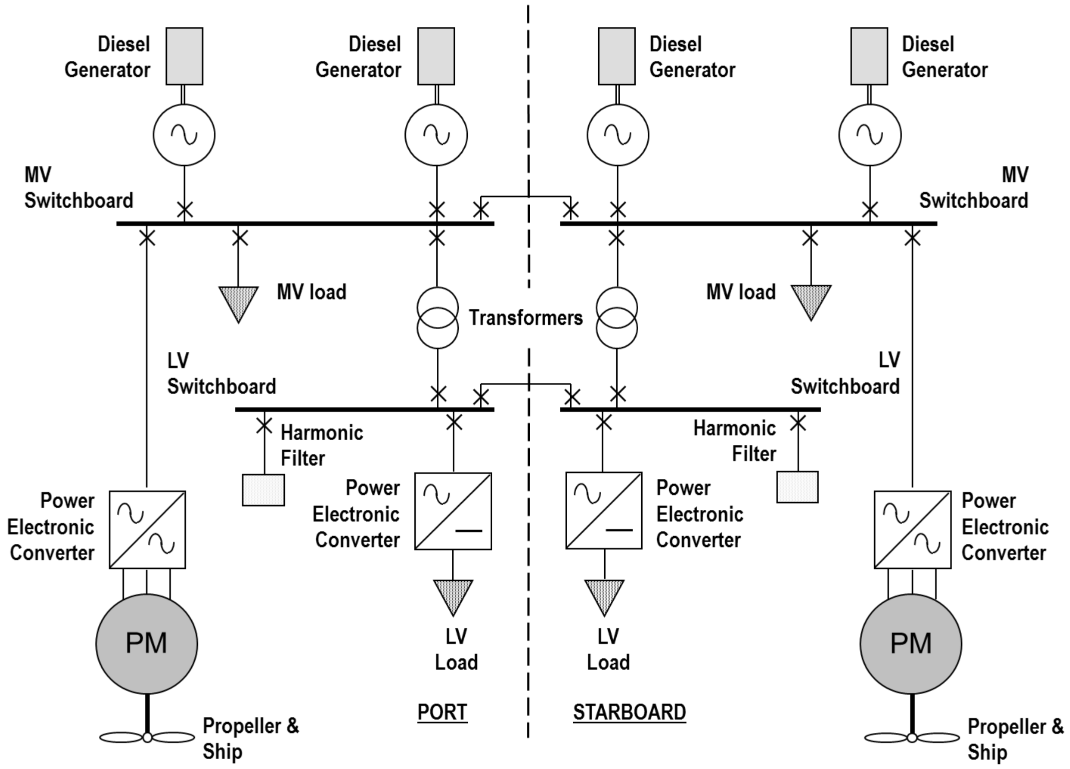


Figure 5-4 IFEP-hybrid AC/DC architecture

Figure 5-5 shows the control loop for the thyristor. The DC voltage V_{dc} is measured and compared with the required DC voltage V_{dc}*. The pulses block regulates the firing angle *a*, which determines the average voltage V_{dc}. The output of the PI controller is limited between 0° and 90° in order to avoid negative V_{dc}.

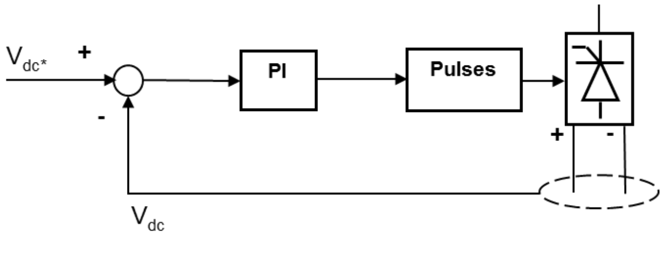


Figure 5-5 Controlloop for thyristor

5.5 Case study – IFEP network architectures

A three-phase short circuit was applied to each IFEP architecture model in order to assess the impact on the power availability and hence vessel survivability. In this study the transient system responses, and in particular the maximum values of system parameters such as peak currents were monitored immediately after the occurrence of the disturbance. The IFEP architecture models were not subjected to post-fault clearance - and system reconfiguration algorithms as these were considered outside the scope of the thesis. The short circuit behaviour case was published in Schuddebeurs *et al* [schuddebeurs07a]. The IFEP-hybrid AC/DC architecture contains a capacitor to smooth the DC voltage. However, this capacitor could potentially feed into a DC short circuit. This phenomenon was investigated using the IFEP-hybrid AC/DC architecture model and was published in Booth *et al.* [Booth08].

5.5.1 Short circuit scenario

The balanced three-phase short circuit (fault), although less common than a single line-earth short circuit, is the most severe type of short circuit and may therefore have a significant impact on the power system performance. In a three-phase fault, the fault currents are balanced and have only a positive-sequence component [Glover02]. The fault current $I_{f\text{-}AC}$ therefore equals:

$$I_{f-AC} = \frac{V_f}{Z_f} \tag{5.3}$$

where V_f and Z_f are the pre-fault positive-sequence voltage and sub transient impedance respectively. As for the IFEP-hybrid AC/DC architecture, a positive-to-negative busbar fault was applied to the LV DC part of the system. In this case $I_{f\text{-}DC}$ can be calculated by:

$$I_{f-DC} = \frac{V_f}{R_f} \tag{5.4}$$

where V_f and R_f are the pre-fault positive-sequence voltage and subtransient resistance respectively. As for the IFEP-radial architecture a three-phase fault was applied 1s after the start of the simulation. The impedance Z_f is calculated as the total impedance between voltage source and fault location. This time-lapse provides a clear distinction between the pre-fault and post-fault system behaviour.

In order to compare the three IFEP architectures with each other, similar parameter values were used as shown in Table 5-1. For this particular study only static MV and LV loads were considered in order to simplify the model without compromising the required fidelity. For the fault current comparison the contribution of the synchronous generation to the fault current was considered appropriate.

Table 5-1 IFEP architecture parameters

Subsystem	*Parameter values*
Synchronous generator	10MVA, 6.6kV
Static MV load	5MW, pf0.85
Static LV load	2.125MW, pf0.85
Transformer (Dyn)	3MVA, 6.6kV/0.44kV
Leakage inductance transformer	0.045p.u.
6.6kV cable (per phase); 10,20m	0.22988 Ω/km
0.44kV cable (per phase); 10m	0.148 Ω/km

With respect to the IFEP-radial architecture Figure 5-6 shows the locations where voltage and current measurements were taken. The three-phase fault was applied to the LV busbar at location *D* 1s after the start of the simulation.

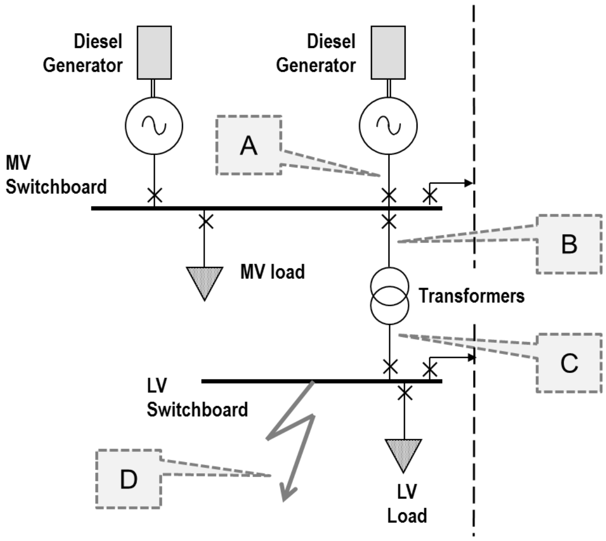


Figure 5-6 IFEP-radial architecture: Measurements and fault location

Figure 5-7 shows the line-to-line voltages at location *A* where the voltage-drop after the start of the three-phase fault is approximately 22%. The three-phase currents at location *A* are presented in Figure 5-8. After the initial peak current, the currents decay to a steady state condition approximately 0.2s after the start of the fault. The currents at the different locations are summarised in Table 5-2 where I_{peak} is the peak current due to the fault and *factor* represents the ratio of I_{peak} over the nominal current. As can be observed I_{peak} is significant at location *B* and *C*, which is close to the fault location *D* and hence has a small Z_f. More current plots can be found in the Appendices.

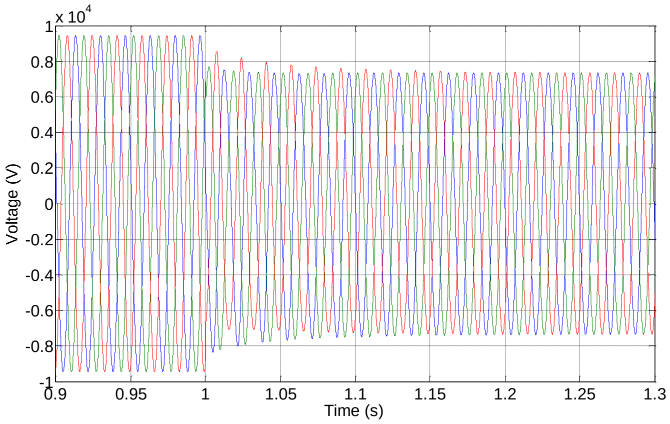


Figure 5-7 L-L voltages at location A

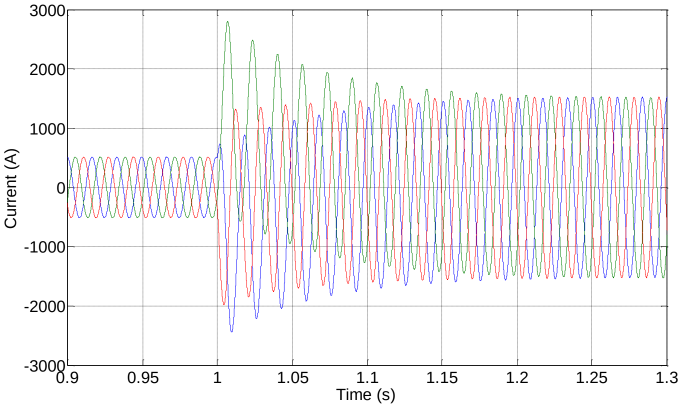


Figure 5-8 Currents at location A

Table 5-2 Peak currents IFEP-radial architecture

Location	*A*	*B*	*C*
I_{peak} (kA)	2.8	5.26	78
factor	5.4	18	17.8

As expected, the corresponding voltage close to the fault location collapses to almost zero due to the virtually zero Z_f. There is also an impact on the MV voltage observed as a significant voltage reduction, but this is buffered through the impedance of the transformer in the fault current path. As with the IFEP-radial architecture the impedance Z_f is calculated as the total impedance between voltage source, i.e. generation-unit, and fault location.

The model for the IFEP-ring architecture is presented in Figure 5-9 where 4 generation-units contribute to the fault current as the network is operating in ring with the tie-breakers closed.

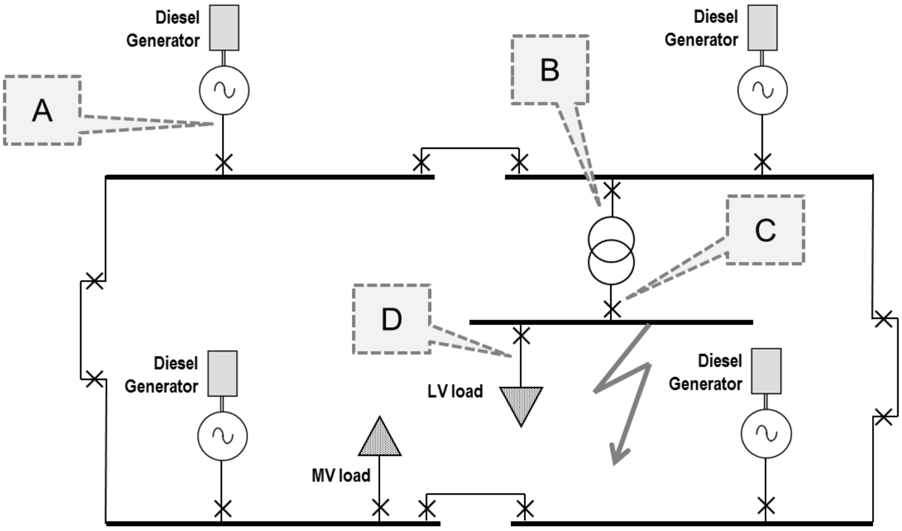


Figure 5-9 IFEP-ring architecture: Measurements and fault location

Figure 5-10 shows the line-to-line voltages at location *A* where the voltage-drop due to the fault is approximately 14%. The three-phase currents at location *A* and the I_{peak} *factors* are shown in Figure 5-11 and Table 5-3 respectively. Similar to the radial case, the three-phase fault occurs 1s after the start of the simulation.

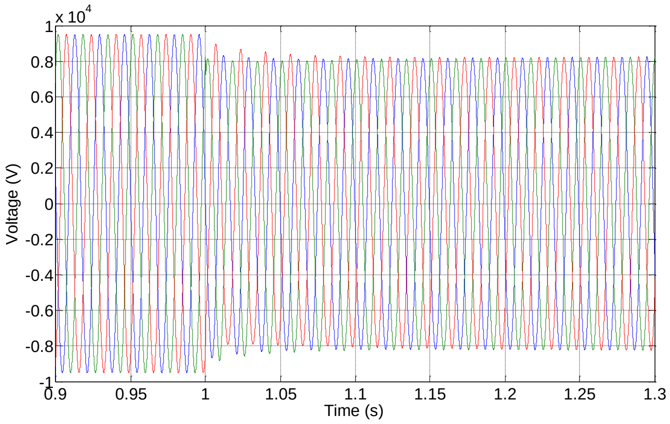


Figure 5-10 L-L voltages at location A

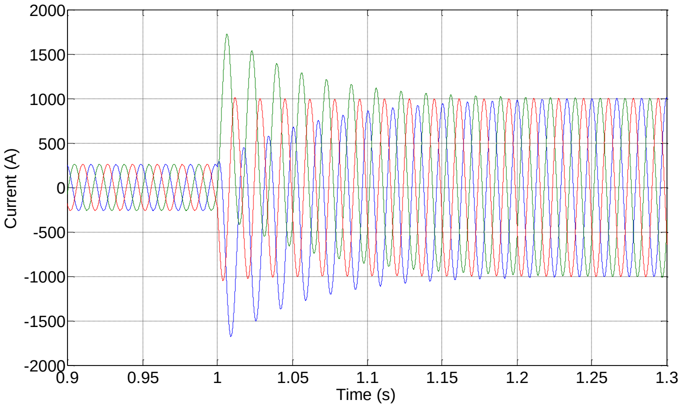


Figure 5-11 Currents at location A

Table 5-3 Peak currents IFEP-ring architecture

Location	*A*	*B*	*C*
I_{peak} (kA)	1.726	6.53	103
factor	6.6	21.8	23.4

The model for the IFEP-hybrid AC/DC architecture is presented in Figure 5-12 in which a capacitor with a value of 0.05F was used to smooth the DC voltage output. The DC fault occurs after 1s into the simulation and is cleared after 100ms.

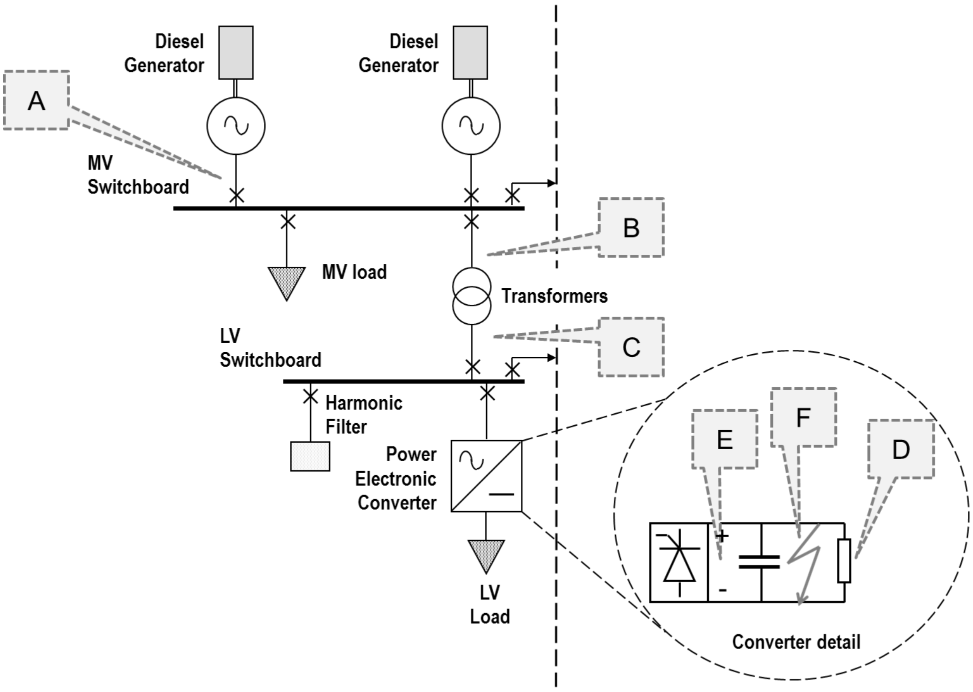


Figure 5-12 IFEP-hybride AC/DC architecture: Measurements and fault location

Figure 5-13 - Figure 5-17 show the voltage and currents at location *A* and *B* respectively. A high peak fault current of 38kA at location *F* is shown in Figure 5-15. This fault between the DC busbars causes the stored energy within the capacitor to discharge into the short circuit. This represent a significant challenge and fault containment, energy dissipation and voltage surge arresting technologies may be required to mitigate against such high-energy discharges. The oscillations in Figure 5-15 are due to the interaction between the capacitance and inductance in the system. Table 5-4 summarizes the peak currents and factors. Note that only the factors for the AC distribution were taken into account as the DC currents considered were the fault currents itself and have no nominal current. The thyristor peak fault currents of 41.6 kA, may cause fuses inside the converter to trip, which may cause spurious tripping and mal-operation of the power system protection. After the fault is cleared at t= 1.1s, the system takes approximately 0.2s to regulate the voltage back to the desired value.

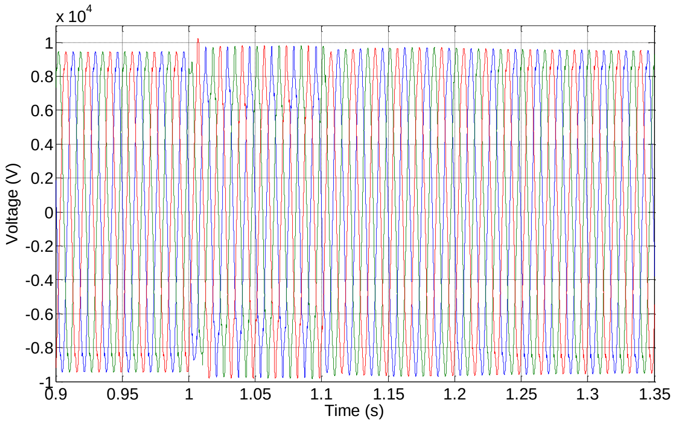


Figure 5-13 L-L voltages at location A

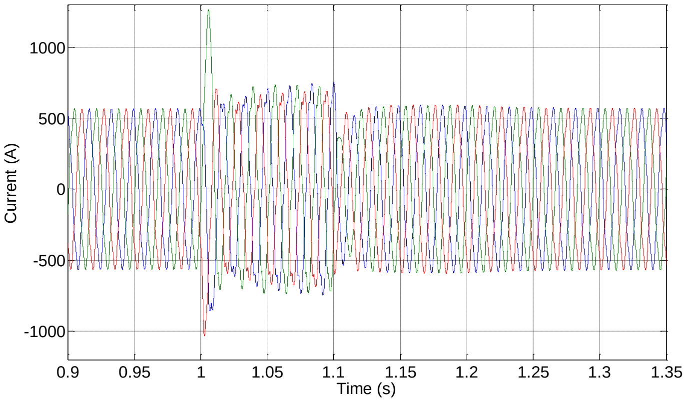


Figure 5-14 Currents at location A

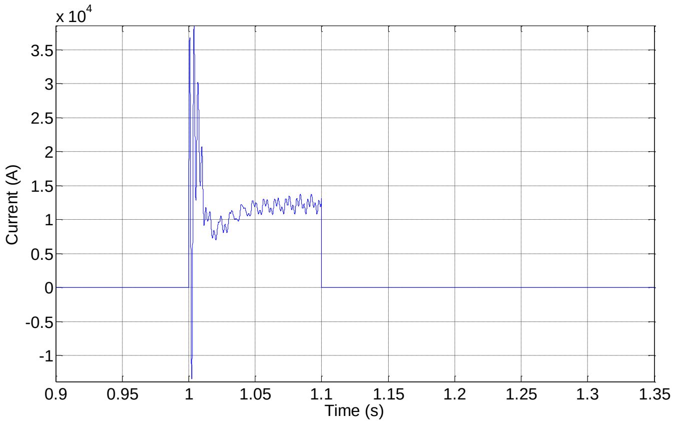


Figure 5-15 Fault current at location F

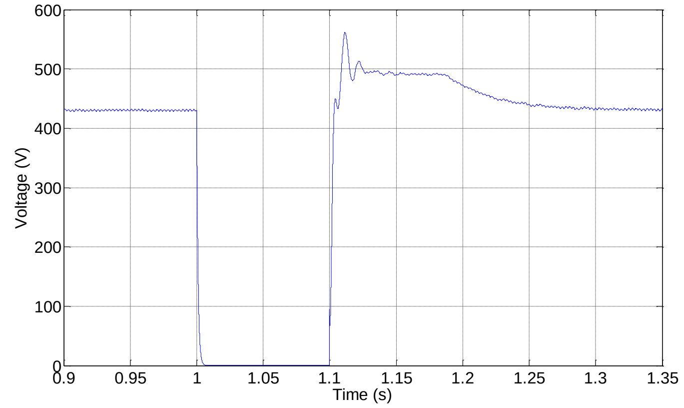


Figure 5-16 DC voltage at location D

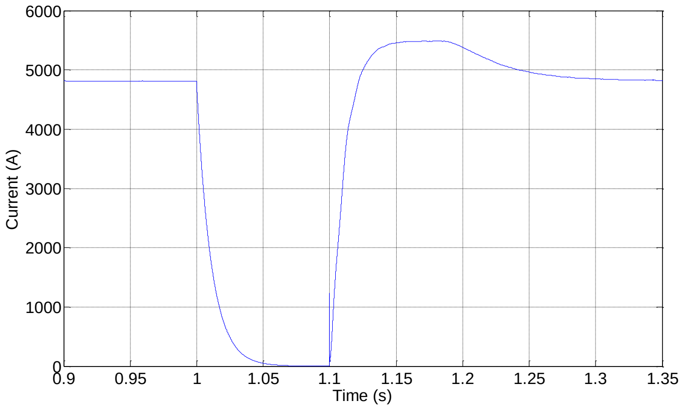


Figure 5-17 DC current at location D

Table 5-4 Peak currents IFEP-hybrid AC/DC architecture

Location	***A***	***B***	***C***	***E***	***F***	***Thyristor***
I_{peak} (kA)	1.26	1.95	26.9	41.5	38.4	41.6
factor	2.2	4.8	5.1	X	X	X

5.5.2 Comparison case study

Comparison of the IFEP architectures was quantified, which is presented next. The values in Table 5-5 are normalised with respect to the IFEP-radial architecture as this architectures is most commonly used. The letters behind each normalised value indicate the measurement location.

In comparison with the IFEP-radial architecture, the peak fault currents on the LV and MV side are higher for the ring network; a factor 1.32 and 1.24 respectively. One of the reasons is an increased number of generators and reduced fault path impedance due to parallelism within the architecture. The IFEP-hybrid AC/DC architecture has a lower LV and MV peak fault current than the IFEP-radial architecture, a factor 0.49 and 0.37 less respectively. The MV load voltage and current drops of 11% and 8% respectively are less than that of the IFEP-radial and IFEP-ring architecture.

Table 5-5 Comparsion currents

Architecture	*IFEP-radial*	*IFEP-hybrid*	*IFEP-ring*
Current levels LV	1 (C)	0.49 (F)	1.32 (C)
Current levels MV	1 (B)	0.37 (B)	1.24 (B)
Voltage drop MV load	18-22%	8-11%	14%

In addition various less measurable aspects can be evaluated using for example discrete quantification values. In this case the system redundancy was chosen as an example of important non-measureable aspects. The discrete quantification used includes the following values and meanings: “1“= poor; “2” = average and “3” = good as shown in Table 5-6. Both the IFEP-radial as well as the IFEP-hybrid architecture was given a value of 2 since both architectures are based on a radial layout, which has limited redundancy. The only difference is the DC distribution on the LV side of the IFEP-hybrid architecture. The IFEP-ring architecture was given a value of 3 as alternative paths can easily be made by closing the tie-breakers.

Table 5-6 Comparison non-measurable aspects

Aspects	*IFEP-radial*	*IFEP-hybrid*	*IFEP-ring*
Redundancy	2	2	3

The survivability state component methodology as presented by Gyparis *et al*. [Gyparis03] is now used to calculate the survivability for each of the three IFEP architectures. According to (5.2) state components P_X and P_V can be assumed equal for all network architectures; meaning vessel survivability P_S equals recoverability P_R. Breaking P_R further down yields the following sub-state components: *mobility systems* (P_{Rm}), *battle systems* (P_{Rb}) and *structural integrity* (P_{Rs}). Apart from P_{Rs}, the power availability may affect the other sub-components P_{Rm} and P_{Rb} as they uses electrical power to operate. By assuming P_{Rs} equal to 1, the resultant sum P_{R_power} equals:

$$P_{R\_power} = P_{Rm} + P_{Rb} \tag{5.5}$$

Assuming further that no difference is made between P_{Rm} and P_{Rb} the survivability P_S can be rewritten as:

$$P_S = P_{R\_power} \tag{5.6}$$

P_{R_power} in the case study is derived and calculated from Table 5-5 and Table 5-6. In order to calculate P_{R_power} from the normalised values in Table 5-5, the following equation is used

$$Z = \left(\frac{1}{n} \sum_{i=1}^{n} \alpha_i x_i \right)^{-1} \tag{5.7}$$

where *Z* is the power system measurement score per IFEP architecture, *n* the number of measurements for which a low value is favourable for the survivability, and *a* the weight per normalised value *x*. For measurements where a high measurement value is favourable for the survivability, (5.7) can be slightly modified into (5.8). The *Z* calculation in Table 5-7 used (5.7) with the assumption that a low fault current is favourable for the vessel survivability. This is true if for example the protection system is sensitive enough to detect the lower fault currents in accordance with the standards. In addition the weight *a* for the normalised value *x* was considered to be equal to 1 but can be adapted if deemed to be required.

$$Z = \frac{1}{n} \sum_{i=1}^{n} \alpha_i x_i \tag{5.8}$$

Table 5-7 Power system measurement score

Architecture	*IFEP-radial*	*IFEP-hybrid*	*IFEP-ring*
Current levels LV	1	0.49	1.32
Current levels MV	1	0.37	1.24
Voltage drop MV load	1	0,5	0,64
Z value	1	2,22	0,93

The total P_{R_power} score is a combination of the *Z* values and the less measurable comparison aspects as summarised in Table 5-8. The aspects values are normalised with respect to the IFEP-radial architecture. In this case the redundancy aspect is added to the Z scores, which yields the final

P_{R_power} scores. Based on these results, it can be concluded that the survivability for the IFEP-hybrid architecture has the highest score followed by the IFEP-ring and IFEP-radial architecture. Since the obtained P_{R_power} value is a relative measure with respect to these IFEP architectures, an absolute survivability score cannot be provided with this method. Therefore, a graph similar to that of Figure 5-1 cannot be constructed.

Table 5-8 Total P_{R_power} score

Criteria comparison	*IFEP-radial*	*IFEP-hybrid*	*IFEP-ring*
Redundancy	1	1	1,5
Z value	1	2,22	0,93
P_{R_power}	2	3,22	2,43

5.5.3 Short circuit behaviour with converter smoothing capacitors

Many present and future marine power systems employ power converters, which are based on advanced solid state technology. These power converters are used for example to supply propulsion motors with a variable frequency supply and to permit the introduction of hybrid AC/DC systems. However, the presence of relatively large smoothing capacitors (DC busbar capacitive filter) associated with converters can lead to very large short-duration fault currents as the capacitors discharge into the fault.

In order to assess the effect of the capacitor value on the DC fault current and voltage ripple, the IFEP-hybrid AC/DC architecture model from the short circuit case was used. A positive-to-negative DC busbar fault was applied at 1s after the start of the simulation and then cleared after 0.1s. In addition to the generation-units, which feeds the fault current, the smoothing capacitor C discharges almost instantaneously into the fault location as well, thereby increasing the maximum fault level even more. The DC busbar currents and voltages of different capacitor values, during fault conditions, are shown in Figure 5-18 and Figure 5-19 respectively. The fault current peak values are summarised in Table 5-9. It can be observed that improved quality of DC supply is achieved at the cost of a higher maximum current into a fault, weight and size of the capacitor. The maximum DC current during the fault ranges from approximately 7 to 9 times the nominal current across the range of smoothing capacitors considered. Breaking these DC currents are more difficult than breaking a similar AC current due to the lack of a zero-crossing current.

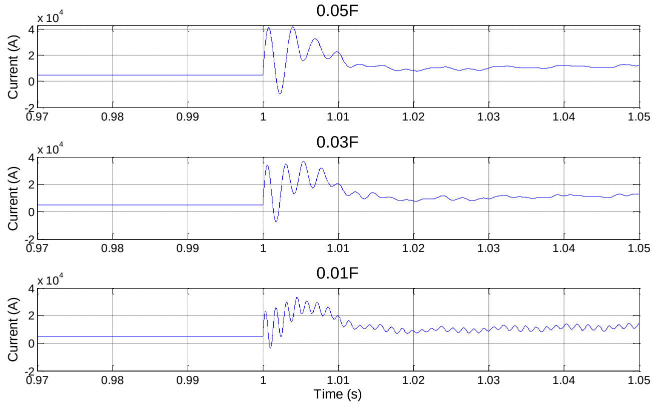


Figure 5-18 DC Bus bar current for different capacitor values

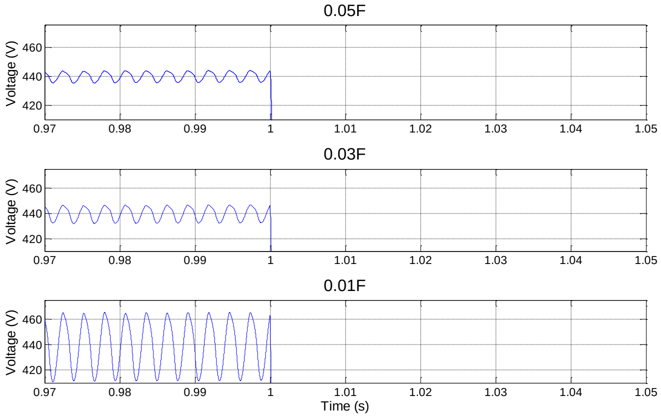


Figure 5-19 DC Bus bar voltage ripple for different capacitor values

Table 5-9 DC busbar fault current and pre-fault voltage ripple

Smoothing Capacitor (F)	*Max fault current (kA)*	*Voltage Ripple (%)*
0.01	33.18	12.7
0.03	36.77	3.7
0.05	41.71	1.9

5.6 Comparison conclusions

Based on the comparison results in Table 5-5, the IFEP-hybrid AC/DC architecture has the lowest peak fault current levels in comparison to the IFEP-radial and IFEP-ring architecture. In addition, the criteria results in Table 5-6 indicate that both the IFEP-hybrid AC/DC and IFEP-ring architecture have an advantage over the IFEP-radial architecture in terms of recovery; although at the cost of a more complex power system protection system. This is particularly true for the DC protection where high fault currents may occur due to the capacitor discharge. However, DC solid state circuit breakers exist [Krstic07], which could be used to reduce the high DC fault currents. Therefore based on these simulation results the IFEP-hybrid AC/DC architecture is preferred.

5.7 Chapter summary

In this chapter a study was presented in which a number of typical IFEP power system architecture philosophies were compared against each other with respect to system responses to disturbances. For this study an IFEP-radial, IFEP-ring and IFEP-hybrid AC/DC architecture were considered as these can be found on present and near future IFEP vessels. While it is difficult to draw authoritative conclusions with respect to the impact of different power system architectures on vessel survivability, it is clear that certain architectures display a higher level of single-fault or outage redundancy. A method was developed, which provides a quantitative way to compare the vessel survivability by focusing solely on the power availability. The case study demonstrated that the IFEP-hybrid AC/DC architecture offers the highest value of vessel survivability during short circuit faults.

Chapter 6 Conclusions and Future research work

The study in this thesis was set out to explore how advanced modelling and simulation techniques can be used to de-risk the design and in-service of complex multi-domain IFEP vessels and how IFEP architecture topologies may affect the vessel survivability. Therefore, the study sought to answer the following three questions:

- Research Question 1 How can complex multi-domain systems best be modelled and simulated while taking into account the required level of model fidelity and the multiple time constants present within these physical domains and subsystem?
- Research Question 2 How can a model, which meets the requirements of Research Question 1, be applied to de-risk the design and in-service of IFEP vessels?
- Research Question 3 How does the architecture of IFEP power systems in general affect the power availability and hence vessel survivability?

The following thesis conclusions address the above research questions.

6.1 Conclusions

The further technological developments of IFEP vessels demand the use of more advanced modelling and simulation techniques.

In 2005 the work for this thesis started. At that time the need to develop techniques to investigate complex multi-domain systems using an integrated-model was not widespread; in particular not within the marine shipping industry. However, recently this idea of an integrated-model for IFEP vessels has received more attention. See for example a paper published by Thirunavukarasu *et al.* [Thirunavukarasu13]. It is most likely that in the coming years more focus of the marine shipping research community will shift towards investigations into complex multi-domain modelling. This will partly be driven by changes within the sector itself; for example the implementation of novel loads, increase of system complexity and stringent classification rules.

In addition recent developments and insights in multi-domain modelling (e.g. Zupančič and Sodja *et al.* [Zupančič11]) and the interest from other industries (e.g. Khan *et al.* [Khan14]) into this subject, will probably accelerate the developments for the marine shipping industry on this matter. Generic research themes, with respect to multi-domain modelling, across the industries may include: *Improvement of computational efficiency, system-wide model validation, model stability, simulation error reduction, reusability of submodels* and *plug-and-play principle of various subsystems*. In light of this likely research trend, this thesis has addressed some of the above research themes by answering the research questions 1 and 2.

By combining and applying present advanced modelling and simulation techniques correctly, complex high-fidelity multi-domain systems (such as IFEP) can be analysed adequately.

The study in Chapter 3 was set out to investigate methodologies to model and simulate complex multi-domain systems in an efficient manner without compromising the required level of fidelity. The need for these methodologies have become more apparent with the increase of more complex multi-domain systems and the requirement to de-risk the design and in-service of these systems. In order to enable investigations into the interactions between subsystems and domains, the use of conjugate variables has been proposed in the literature. In the electrical domain these are for example the effort variable "voltage" and the flow variable "current". However, these conjugate variables may form loops where an input to a subsystem is at the same time a function of its own output. From literature and the experience with the AMEPS model it is known that these loops can be solved by inserting a one time-step time delay in the loop.

Although multi-rate simulation improves the computational efficiency of complex multi-domain models significantly, errors due to multi-rate simulation provoke unrealistic subsystem responses.

For the AMEPS model (an example of a complex multi-domain IFEP model) significant reductions in simulation execution times were achieved using multi-rate simulation. The smallest time-step of 5μs was only applied to the rectifier model in the electric drive and the electrical distribution system. The rest of the system was simulated with much higher time-steps (400μs and 1ms). As a result an improvement of 15 times was observed – this in contrast to models in the literature, which have more modest improvements. However, if more submodels are implemented with a 5μs time-step, such as high-fidelity electric drive models, the speed improvement may be less than 15.

Although significant reductions in simulation execution times were achieved with multi-rate simulation, potential errors could propagate itself across the entire system. This may be due to latching of the slow subsystem onto fast phenomena, occurring in the fast subsystem, at the moment of data synchronisation. These errors could provoke responses from various subsystems, which are different from the error-free case. For example benign responses of gas turbines cannot be assumed. The effect of latching can be reduced using either natural filtering or a low-pass filter. The former is preferred as no artificial source of error is introduced. However, a low-pass filter may still be required in case of disturbances close to the natural filtering boundary. In that case the time-step of the slow subsystem may need to be reduced in order to reduce the error at the cost of computational efficiency. Quantification of the propagated latching error will contribute to a more formal trade-off between computational efficiency and benign system responses. Natural filtering was successfully applied to all the fast-to-slow boundaries in the AMEPS model.

A combination of several validation techniques for complex high-fidelity models provides satisfactory results.

A combination of different validation methods applied to the AMEPS model worked out well in order to increase the validity. Individual submodels were validated using for example predictive validation and face validation. It was demonstrated that face validation is a crucial step when conducted by subject-matter-experts (SME) despite the fact that face validation is not a quantitative method. In particular since rigorous system-wide validation methods are lacking (not considering full test-rig validation), face validation was found to be the best practical solution for system-wide validation.

Advanced modelling and simulation techniques can be used to adequately de-risk the design and in-service of IFEP systems

Based on techniques such as multi-rate simulation and conjugate power variables, a typical IFEP system (the AMEPS model) was modelled at an adequate level of fidelity. It was demonstrated that this model provides a unique modelling and simulation platform, which enables investigations into for example the complex subsystem interactions during a load change. A case study in which a significant load step and cyclic loading on the propeller was investigated, demonstrated the propagation of disturbances across the entire IFEP system. For example, it was shown that the gas turbine governor ran into saturation due to a significant load change at the propulsion motor side. Insights into these higher order responses, such as saturation in this case, can help ship designers to develop more optimized overall control strategies. This analysis in the time-domain can be considered complementary to the more common control analysis in the frequency-domain.

Although the present model and case study offers already new insights, there is further potential since a more realistic IFEP system consists of multiple prime movers, multiple propulsion motors or even novel loads such as rail guns. Therefore, modelling and simulation platforms such as the AMEPS model will help ship designers to investigate the complex interactions between all these subsystems and develop related control strategies.

The IFEP architecture topology has a significant impact on power availability and hence vessel survivability.

The choice of a particular IFEP architecture topology has a significant impact on the power availability and ultimately on the vessel survivability in case of for example disturbances on the grid. Comparison of different IFEP architectures with respect to survivability has only recently received attention from the marine shipping industry. For example Chalfant and Chryssostomidis [Chalfant11] report on the ESRDC efforts in MVDC developments for naval vessels. In this thesis a case was demonstrated in which an IFEP-radial, IFEP-ring and IFEP-hybrid AC/DC architecture were compared against each other from a power system behaviour point of view. Both simulation outputs (such as fault current levels) as well as non-measurable aspects (such as system redundancy) were used in the comparison evaluation. For this evaluation an existing vessel survivability theory was adopted, further developed and used. Based on this evaluation, it was concluded that the IFEP-hybrid AC/DC architecture offers the best survivability score mainly due to its relatively low fault current levels. The work in this chapter is not only applicable to the military shipping industry but to the marine shipping industry in general and has answered research question 3.

6.2 Future research work

Multi-rate error propagation

Although the conceptual idea of error propagation due to multi-rate simulation was discussed thoroughly in Chapter 3, quantification of these errors would be useful. For example this quantification makes a more informed trade-off possible between the various time-steps sizes, filtering method and model fidelity level. Therefore, further investigations into this matter are recommended.

System-wide validation

A sound system-wide validation methodology (no full test-rig validation) for an integrated model, which also validates the complex interactions between the subsystems, is lacking. As the development of more complex high-fidelity models is growing, further studies on this system-wide validation is recommended.

Vessel survivability

The survivability score, which was developed in this thesis, is in the present form greatly influenced by the fault current levels and the system redundancy score. More “aspects”, with clear distinct performances between the IFEP architectures, should be added to the calculation to improve the accuracy of the survivability score.

The integrated-model developed under the AMEPS project and the work conducted in the power system architecture comparison study, can be combined. This may for example lead to complex high-fidelity IFEP models, which are capable of both complex multi-domain studies and survivability calculations.

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Appendices

A.1 Ordinary differential equations

The dynamics of a system can in general be described [Günther01] by an Initial Value Problem (IVP) of Ordinary Differential Equations (ODE) in the form of:

$$y' = \frac{dy}{dt} = f(t, y), \qquad y(t_0) = y_0, \qquad y \in R^n \qquad (\text{A.1})$$

where y is the dependent variable and t the independent variable. As opposed to ODEs, which involves only one independent variable, Partial Differential Equations (PDEs) contain two or more independent variables and are of the general form [Chapra06]:

$$f(x, x', w, u, t) = 0 \qquad (\text{A.2})$$

where x, w, u and t are a vector of state variables, algebraic variables, vector inputs and time respectively. A large number of numerical methods exist to approximate the exact solution of functions, which cannot be solved analytically [Chapra06].

A.2 Truncation errors

Taylor's Theorem states that any smooth function can be approximated by a polynomial. This can be expressed in (A.3) where the right side of the equation is a Taylor polynomial approximation to *f*(x_{i+1}) [Chapra06].

$$f(x_{i+1}) \cong f(x_i) + f'(x_i)h + \frac{f''(x_i)}{2!}h^2 + \frac{f^{(3)}(x_i)}{3!}h^3 + \ldots + \frac{f^{(n)}(x_i)}{n!}h^n \tag{A.3}$$

In (A.3) *h* is the time-step and can be expressed as:

$$h = x_{i+1} - x_i \tag{A.4}$$

Adding a derivative remainder term R_n to the right side of (A.3) yields the exact solution as expressed in (A.5). This equation is also known as the Taylor series.

$$f(x_{i+1}) = f(x_i) + f'(x_i)h + \frac{f''(x_i)}{2!}h^2 + \frac{f^{(3)}(x_i)}{3!}h^3 + \ldots + \frac{f^{(n)}(x_i)}{n!}h^n + R_n \tag{A.5}$$

The general form of R_n can be expressed as:

$$R_n = \frac{f^{(n+1)}(\xi)}{(n+1)!}h^{n+1} \tag{A.6}$$

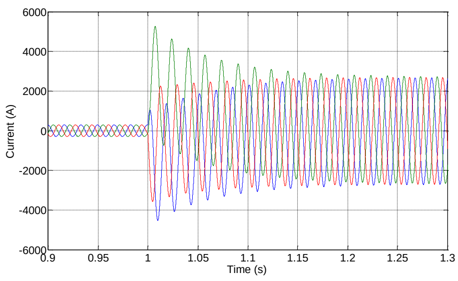
R_n is useful as h can be controlled. For example h^2 implies that halving h will quarter R_n. A more common expression for R_n is [Chapra06]:

$$R_n = Oh^{n+1} \tag{A.7}$$

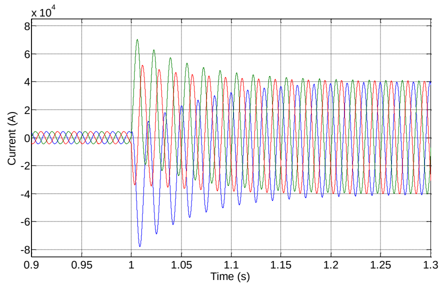
A.3 Simulation results IFEP architectures

The following results are from Schuddebeurs *et al.* (Schuddebeurs07a)

IFEP-radial architecture: three-phase fault

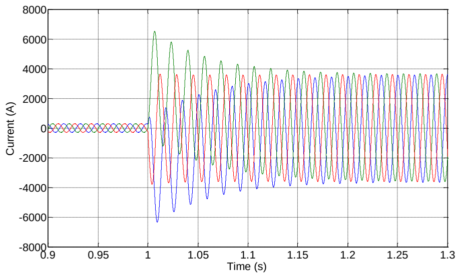


Figure_Apx 1 MV currents at location B

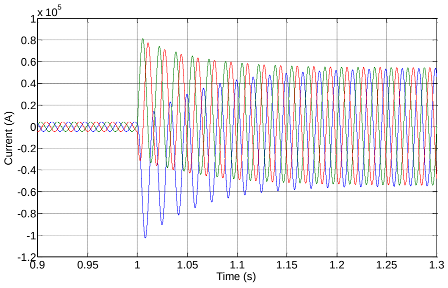


Figure_Apx 2 LV currents at location C

IFEP-ring architecture: three-phase fault

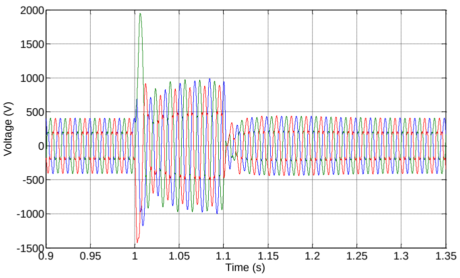


Figure_Apx 3 MV currents at location B

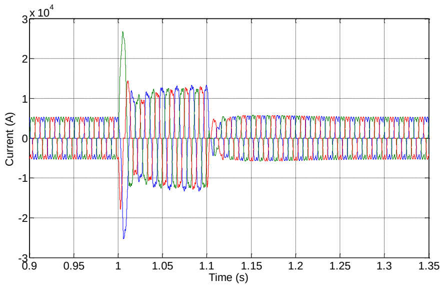


Figure_Apx 4 LV currents at location C

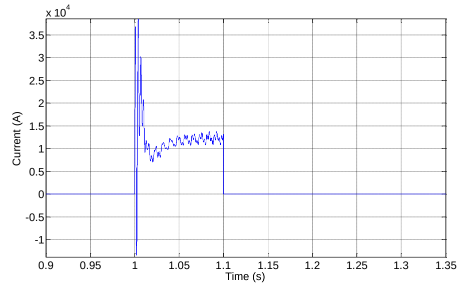
IFEP-hybrid AC/DC architecture: three-phase fault



Figure_Apx 5 Currents at location B



Figure_Apx 6 Currents at location C



Figure_Apx 7 Fault Current at location F