Marine Propulsion System

نظام الدفع البحري

by

HANAN AHMED AL SHARIF

A dissertation submitted in fulfilment

of the requirements for the degree of

MSc SYSYEMS ENGINEERING
at

The British University in Dubai

Professor Robert Whalley
September 2017

DECLARATION

I warrant that the content of this research is the direct result of my own work and that any use made in it of published or unpublished copyright material falls within the limits permitted by international copyright conventions.

I understand that a copy of my research will be deposited in the University Library for permanent retention.

I hereby agree that the material mentioned above for which I am author and copyright holder may be copied and distributed by The British University in Dubai for the purposes of research, private study or education and that The British University in Dubai may recover from purchasers the costs incurred in such copying and distribution, where appropriate.

I understand that The British University in Dubai may make a digital copy available in the institutional repository.

I understand that I may apply to the University to retain the right to withhold or to restrict access to my thesis for a period which shall not normally exceed four calendar years from the congregation at which the degree is conferred, the length of the period to be specified in the application, together with the precise reasons for making that application.

H.AlSharif

Signature of the student

Abstract

The research is an application of a multivariable system control for marine propulsion system where the propeller pitch is controlled to reach stability within different conditions and disturbances. Attention is paid also in fuel consumption in order to reduce the pollution via environment and cost reduction by improving the engine speed control.

This dissertation is done on the marine propulsion system model that has been solved mathematically first and then testing the stability of the model using MATLAB/ SIMULINK software. By modeling the ship propulsion system it becomes easier to understand, what parameters are affecting the system and how to control them.

The first part of the research is about an introduction of the marine propulsion system. The research problem states a model of multivariable control system for a propeller pitch with two inputs and three outputs. These are the fuel flow rate and the cylinder area controlling the torque and thrust that affects the ship speeds. The method used in this controller is the least effort technique as from the previous control dissertation this method is producing maximum stability, producing best performance and acting as best method for disturbance recovery.

As mentioned above and concludes in this research after simulating the model, the least effort control technique shows the best performance and disturbance recovery using the simplest controller. These are the reasons of implementing it in many applications at the main time and the marine propulsion system a good example of the least effort technique application.

خلاصة البحث

البحث هو عبارة عن تصميم لنظام تحكم ذو متغيرات متعددة وتجربة تطبيقه على نظام الدفع البحري، حيث يتم التحكم بمروحية الدفع للوصول إلى حالة الاستقرار بسرعة في ظروف ومتغيرات داخلية وخارجية مختلفة. ويولى الاهتمام أيضاً في استهلاك الوقود من أجل الحد من تلوث البيئة والحد من تكاليف استهلاك الوقود عن طريق تحسين التحكم في سرعة المحرك. تتناول هذه الأطروحة تصميم نظام الدفع البحري بدءا بحل المسألة رياضياً وإيجاد المعادلات المطلوبة، ومن ثم اختبار استقرار النظام باستخدام برنامج MATLAB/SIMULINK. من خلال تصميم وتنفيذ نظام الدفع للسفن يتمكن المصمم معرفة المتغيرات التي تؤثر على سرعة المحرك سواء كانت داخلية أو خارجية وكيفية السيطرة عليها.

الجزء الأول من البحث عبارة عن مقدمة لنظام الدفع البحري. أشارت مشكلة البحث إلى تصميم مروحية الدفع والتي لها مدخلين وثلاث مخرجات لنظام التحكم متعدد المتغيرات، المدخلات عبارة عن معدل تدفق الوقود ومنطقة الأسطوانة والتي يتم التحكم بها للسيطرة على عزم الدوران والقوة والتي تؤثر على سرعة السفينة. والطريقة المستخدمة في وحدة التحكم هي تقنية أقل جهد والسبب في اخيار هذه التقنية هي في انتاجها أقصى قدر من الاستقرار، وإنتاج أفضل أداء والعمل كأفضل طريقة لاستعادة الاضطراب وذلك حسب الدراسات القديمة في مجال أنظمة التحكم ذو المتغيرات المتعددة.

كما ذكر أعلاه وفي خاتمة البحث بعد تصميم وتنفيذ النظام، فإن تقنية التحكم الأقل جهد تظهر أفضل أداء واستعادة النظام لحالة الاستقرار بعد الاضطرابات بأبسط وحدة تحكم. وعليه فإن الأسباب المذكورة كفيلة بتنفيذ التقنية في العديد من التطبيقات في وقتنا الحالي ونظام الدفع البحري مثال جيد على تطبيق هذه التقنية.

Acknowledgment

My Thanks and appreciation to Professor Robert Whalley for his full support and guidance during my study and dissertation period at the British University in Dubai. In addition, thanks to Dr. Alaa Ameer for being our tutor for the whole study period and my gratefulness extend all the staff and management personnel at the BUID for their support.

Dedication

To my grandmother who loved me.

To My Father and Mother who helped in all my life steps.

To my Family who supported and encouraged me.

To my all the people and colleagues who advised and helped.

I dedicated my work to all of you

List of notations and Abbreviations:

A	state space matrix
B	State space matrix
C	State space matrix
C	Controllability test matrix
C(s)	Transfer function of compensator
D	State space matrix
$D_i(s)$	Diameter of Gershgorin circle
D_P	Diameter of propeller
e(t)	Error signal
F	Outer loop feedback array
F	Thrust deduction
f_i	Gains of feedback
G(s)	Transfer function
I	Polar movement of inertia
i	Number of iterations
j	Imaginary values
J	Performance index
J	Propeller coefficient

$k(s)$ Forward path function

$K(s)$ Input of Inverse Nyquist Array method

F Matrix having all elements as zeroes

$\widehat{H}(s)$ Close loop transfer function

h_{ii} Diagonal terms of inverted closed loop transfer function matrix

$K(s)$ Forward path controller model

L Laplace transformation

m_f Fuel rate flow

n Speed of engine

N_{qi} Number of origin encirclements by the mapping D-contour

N_H High pressure

N_L Low pressure

N_{hi} Number of origin encirclements by the mapping D-contour

N_{qi} Number of origin encirclements

P Solution of Ricatti matrix

P / D Pitch to diameter ratio

P_b Brake power

P_{inl} Pressure in inlet

P_{rc} Pressure in compressor

Q States weighing matrix

Q_p Load torque

Q(s) Open loop transfer function matrix

Q_{ij} off diagonal terms in inverted open loop transfer function

r Radius

R Inputs weighing matrix

R_s Resistance of ship

s Displacement

t Coefficient of thrust deduction

T Time period

T_c Temperature of compressor

T_p Ship thrust and torque

u Fuel index

u(t) Outputs vector

V_A Advance speed of ship

V_s Ship velocity

y(t) Output vector

Z Number of blades in propeller

Z_c Number of right-half complex plane zeroes for closed loop system

Z_o Number of right-half complex plane zeroes for open loop system

λ	Eigen value
θ	Observability test matrix
ω	Angular displacement
π	pi constant
∑	summation
BMEP	Brake Mean Effective Pressure
kWH	Kilo-watt hours
LQR	Linear Quadratic Regulator
MW	Megawatt

List of figures:

TABLE OF CONTENTS

Chapter 1 – Introduction

Nowadays two-stroke marine diesel engines are mostly controlling the marine ship propulsion system. These types of diesel engines are currently the leading type of prime mover being widely used for propulsion today. The reason of using it is for its benefits such as highly efficient, engine ability of working in slow-speed due to the burning of heavy fuel and oil connection directly to the propeller without the need of gearbox and clutch (Balashov, 2011). It is important to mention that for having safe operation of the engine there must be complete control on the revolution of propeller and ship speed accordingly. For example, if the engine is operating at maximum value, rough sea can cause problems to the engine such as over speed will lead to engine damage. Hence, complete awareness is required of the factors that have an impact on the speed of engine for gaining robust control. In case of the propulsion system misalignment, this cause lots of damage to human as well as environment so the recommendation is to avoid propulsion loss. Furthermore, as the strict pollution regulations and high oil prices are currently present, it is important to have complete control of the engine (Li, etl.al, 2013). For the above-mentioned reasons, scientists compete to build the best propulsion system free of defects stated above.

1.1 Research background:

Nowadays, all the aspects of modern society concerns about the energy consumption. The reason of that is fuel cost increment and the environmental worries. According to the research of Gully (2012) the marine industry is responsible for the consumption of fuel each year which is estimated as 3.6 billion barrels of fuel every year. This feeding of fuel is also causing high pollution because of the chemical, industrial and others waste, which is affecting the environment and the researcher are always looking to increase the efficiency and decrease the fuel consumption that is happening in the marine area. For that reasons, the recent designs histories of the naval and commercial vessels are in such a way that meets the requirements of propulsion and electrical loads (Kawamura, Ouchi and Nojiri, 2012).

1.1.1 Naval propulsion system background:

The surface ships used in most of the world operate on the petroleum-based fuels, whereas the sub-surface vessels utilize nuclear power systems. The current developments in the field of powertrain technologies used on the ships work based on the aim of reducing the cost of fuel, as well as, generating more electric power in order to meet the weapon system load in the future (Petersen, et.al, 2010). Therefore, these concerns are leading to the development of the ship by using the integrated power system (IPS). Using the phenomenon of IPS, US has developed the first Navy warship named as DDG-100. The research and development of this ship took more than 10 years and the ship embodies the technological leap forward from the past systems. In 1920s, the US Provide fleet electric ships that operates using the steam engines. Hence, DDG-1000 electric drive systems are the first that made the use of power electronics.

On the other hand, the research of Balashov (2011) presents that the idea of an electrical drive in the propeller of propulsion is not new, as at the end of 19th century in some countries such as Russia and Germany the experiments aim was designing the vessels with electrical propulsion system. The first workable example of the electric ship named as river tanker or “Vandal” and built in 1903 in Russia. That power system consist of three DC generators of 87kW that is operating at 500V. In addition, the prime movers drive the power system which contains the 89.5kW diesel engines and operates at 250 rpm each, with the DC motor connected to the shaft of the propeller. The power transaction done using cables, as well as magnetic clutches that are between the DC generators and the diesel engine. The control operates by excitation adjustment, the ship have good manoeuvrability and the operation time from full ahead to full reverse takes 8-10 seconds.

In spite of all the advantages, this electrical system have power losses that is estimated as 20% of the transmission power. For example, from the 290kW of the output from the diesel, only 216kW found on the screws, without considering the diesel-engine losses. Another reason of not using diesel engines is that they are not reversible which significantly affects the manoeuvrability.

In 1906, the invention of two-and-four stroke directly reversible diesel engines took place and immediately came into production. After that, all the attraction of bulky electric system seems to be gone. That diesel engine helped in gaining higher efficiency by not wasting any energy of the electrical generation, distribution and consumption of electrical energy in the propulsion system. However, from 1920 a new interest came to the diesel-electric configuration due to high requirements of torque on the shaft of the propeller especially when the propeller is surrounded by ice. In 1930, the first icebreaker comprising of electrical power system was built by SISU where the speed of the driving motor altered by switching to a very low inducing current and present in the generator. In 1930's Stromberg began to work on all the ranges that directed towards designing and building the ships with the electric propulsion system and in 1939 the first diesel-electric icebreaker took place and the number increased to 80 and powered by ABB. The other vessels that were built with EP were even more in numbers. The latest revival in electric propulsion systems seen in the 1980s, when the integration of information technology and power electronics began to develop intensively. The modern technology of power electronics drives widely used now due to wide range speed options, controllable propulsion motors, high reliability, high space equipment and good cost-competitiveness (Hansen and Wendt, 2015). Today the propulsion of ship is not just about moving the ship in the water; it also includes the implementation of the best propulsion system for ensuring the best safety standard along with cost efficiency.

There are different types of propulsion system that are available for the ships i.e. diesel propulsion system, wind propulsion system, nuclear propulsion, gas turbine propulsion, fuel cell propulsion, biodiesel fuel propulsion, solar propulsion, steam turbine propulsion, diesel-electric propulsion, water jet propulsion and gas fuel and tri-fuel propulsion. These propulsion systems are explained briefly in the literature review part highlighting the benefits and drawbacks, as well as the systems that are currently being preferred by the ships according to their needs. Some propulsion systems have become obsolete but still used in the ships due to their benefits for that reason all the types are discussed in the literature.

1.2 Research problem statement:

This research based on the project work of Balashov (2011) in which he developed a model of two strokes marine diesel engine. This model called mean value engine model and it calculates the states of the engine based on the average of the obtained value over one engine cycle. The aim of his work is to develop a simple model of the marine propulsion system but at the same time capture the essential system properties. The model needed to represent engine speed, fuel consumption, turbocharger speed and transient air-to-fuel ratio. A simple transfer function from fuel to engine speed does not possess this capability. Moreover, an advanced simulation model of three dimensions becomes too complex, with addressed numerous parameters and heavy computational weight. The mean value model acts as intermediate between these extremes and it is a good choice for controller basis.

In the mean value approach, the slowest dynamics seen as constant and the fastest dynamics of the engine are neglected. Energy and mass in the control volumes considered as homogeneous. An assumption that the fuel and airflow are continuous; meaning that discrete nature of real engine is simplified. Therefore, the independent variable is time and the crank-angle degree needed for modeling discrete events of the engine. The model of the engine divided into different subsystems; the compressor, cylinders, turbine, intake manifold and exhaust manifold. Each part modeled using physical principles and information exchanged between them by the means of flow of mass and energy.

Although the performance of the engine model was decent, the model of the turbocharger shows inadequate behavior. This is due to the fact that compressor flow data is not available leading to the generalized approach of compressor flow rate modeling. As a result, the exhaust and intake multiple pressure become unrealistically high and airflow rate as well. Consequently, the supply of air to cylinder found out abundant and perfect values for combustion were attained independent injected fuel, this phenomenon leads to dynamics of turbocharger being irrelevant for the engine performance. For the real engines, the time response of turbocharger is very important for the supply of air to the engine that produce the engine torque. This problem gives an incentive for modeling the turbine and compressor more accurately. Therefore, the turbocharger examined thoroughly in this dissertation for achieving the overall reasonable engine performance.

Often the encountered literature focussed on either torque absorption or torque production. Thus only highlighting one part of the problem of deciding engine speed. In the sources where turbocharger and engine are adequately described, the load is overlooked or the propeller is always assumed to match the theoretical propeller load curve, however, this is only correct for a limited number of operating factors i.e. no heavy weather, no propeller losses, no hull fouling and no large acceleration. Therefore, the real propeller curve is too crude to represent the real operating conditions. In addition, literature related to propeller modeling rarely reflects the system rotation of the propeller. For this reason, the dissertation will serve as an important factor in consolidating and collecting the information from different literatures and producing the reference of ship propulsion in total.

1.3 Research aims and objectives:

This dissertation is about a marine propulsion system model which will be solved mathematically first and then the stability of the program will be checked on the MATLAB software. By modeling the ship propulsion system it becomes easier to understand what parameters are affecting the system and how to control them. Furthermore, a testing environment such as MATLAB needed for testing possibilities in real-time because testing on real engines is very limited for the reason of the cost involved in buying and installing a two-stroke marine diesel engine is very high. Moreover, the power output and sheer physical size of the largest engine makes it time-consuming and difficult to set up properly testing facility. Therefore, the use of MATLAB models simulation of the engine for describing the engine behavior is essential in understanding how different parameters are creating an impact on the system. The experimental investigation of the engine behavior for the most part prohibited; hence, one cannot simply conduct live testing on the ship because it contains the risk of human loss as well as environmental damage by unstable control of the engine. Consequently, the use of simulation software for finding out the transient response and stability of the system becomes utmost important. The dissertation must be able to represent the engine’s steady state operations as well as transient response.

The propulsion system of the ship is very complex as it carries the influences from different sources some of them are turbocharger, engine, propeller, and ship; hence, it will not be enough to study the behavior of the engine alone. To understand the correct behavior of the system it is important to understand how the turbocharger works and calculate the amount of air it provides to engine's cylinders for combustion. If the modeling of the turbocharger is incorrect, then the amount of air in the cylinder will be wrong, the engine torque will also be incorrect due to combustion efficiency and air-to-fuel ratio. If the torque of the engine is erroneous then most likely, the system is not stable and faulty. Thus, controlling the ship shaft speed will suffer. Focussing on the torque production alone is, however, not enough for the control of engine speed. The researcher must also have the knowledge of the propeller load in varying conditions of the sea, such as in low-depth water and in inclement weather conditions. This also requires the knowledge about the propeller's speed of advance.

As the load of the propeller is dependent on the square of speed's shaft, will suppose that the system is completely stable and believe that the engine over speed will not occur. However, there is a possibility of sudden torque loss. For example in the case of big wave torque loss is usually due to the emergence of the propeller. When the engine is running at the maximum speed than the loss of load torque may lead to engine damage. For this reason, it is important to develop a robust speed controller for these conditions involving severe propeller load fluctuations during the sea and weather disturbances.

In normal situations, to increase the life-spam of the engine, the speed need to be decreased and controlled in a situation of fluctuations caused by propeller load. For retaining the desired ship speed under these circumstances the engines are often oversized, which means that the engine used is larger than what is needed for the normal operating conditions is fitted on the ship. With the availability of oversized engine, a power margin is available for different situations, and the problem of over speed is controlled. However, the oversizing of engine carries some other problems such as lower efficiency, fuel consumption increment, more pollution, extra engine room space and leads to higher installation, maintenance and running costs. The ultimate goal of the dissertation is to solve the control problem in such a way that no speed reduction and engine oversizing appropriately needed in any weather conditions.

1.4 Research dissertation organization:

Chapter 2: Chapter 2 in general is literature review of the previous work in the field of Marine propulsion. It will provide the necessary theoretical background of hull resistance, propeller properties, and engine operations. A short description of turbocharger map is also given.

Chapter 3: Chapter 3 is a research methodology based on a mathematical model that is tested using the software MATLAB and then find out the transfer function to check the stability of the system.

Chapter 4: Chapter 4 is the discussion of the results obtained from the simulation of the program on MATLAB and the stability that found out by using different methodologies.

Chapter 5: Chapter 5 is the conclusion of the dissertation and discusses the advantages of the new model of the marine propulsion system and recommendations for the future work and development.

Chapter 2 - Literature Review

2.1 Introduction:

It is very important to understand the basic components of the marine propulsion system. This chapter is a discussion of marine propulsion system that discuss the hull resistance, thrust losses, characteristics of the propeller and how this affect the engine showed using load diagrams and engine layout. The literature review also analyze the components in a sequential manner by highlighting the theories and design in the industrial of marine propulsion system. The governors that are involved in marine propulsion system mostly design the experimental process models by neglecting the influence caused by hull deformation (Karlsen, 2012). These governors neglect the uncertainty of the marine propulsion system and work fine in the speed control of small-scale ships. On the other hand, as the shipping industry is developing rapidly large vessels such monsters tankers/mammoth tankers, mining and storage areas for marine resources are getting bigger and bigger in size this is leading to an increase in the interaction between the hull and propulsion system.

2.2 Marine propulsion:

There are common idea of how a load of propeller acts in order to control revolutions of marine diesel engine. In the case of marine propulsion, the forward thrust caused using the power setting of the engine that leads to rotating the propeller in water. As a result, water is able to exert a torque on the propeller while rotating. For maintaining the desired speed, it is required to maintain the engine torque and power output to produce the needed estimate value on propeller load. The propeller load always related directly to the design of the propeller and the ship's load and resistance encountered by the ship. Furthermore, the resistance depends on the wear and hull form as well as the external forces such as currents, waves, and the wind (Theotokatos and Livanos, 2013).

2.2.1 Hull resistance:

The hull resistance is the acting forces on the hull against the movement of the marine. This resistance force reduces the effect of the forces produced by the propulsion devices that results in reduction of ship speed. To make a good decision on which engine and propeller to use (power output), then the knowledge of what forces will be present against the propulsion should be clear (Liu, Papanikolaou, and Zaraphonitis, 2011). The resistance of marine is mostly dependent on different factors such as speed of the vessel, displacement and hull form. If there is a case where ship having more streamlined body then it will create less resistance (Seo, et.al, 2010). Hull resistance is further dependent on three more resistances that are:

Frictional resistance

Residual resistance

Air resistance

The frictional and residual resistance affected by the increment submergence of the hull. Nonetheless, not all of the frictional resistance caused by water but also the above part of the ship affected by the air resistance. There is definitely more drag beneath the water due to the fact that water is denser than air (Liu, Papanikolaou, and Zaraphonitis, 2011). The submergence of the hull measured by indicating the amount of water that displaced by the hull, either in the form of weight or volume, and this is called displacement of the ship. These resistances are shown below in figure 2.1 and the explanation of each resistance as follows:

Frictional resistance (R_f) is the resistance gained from hydrodynamic friction present on the hull when the ship is moving in the water which increases approximately double the speed of the ship. There are different techniques that can increase the hull resistance such as degradation of the smoothness of hull by erosion, growing the organism of marine and buckling the bottom plates (Papanikolaou, 2010).

Residual resistance (R_w) is the resistance that includes the wave and eddy resistance (RE). Wave resistance observed as the energy that is lost when the waves generated and ship interacts with them. Furthermore, the water swirling and creation of reverse current when the ship moves through a viscous fluid, particularly at the shaft of the ship regarded as eddy resistance. This effect observed as large rocks in the speedy rivers (Seo, et.al, 2010).

Air resistance (RA) is the resistance that comes from the motion of the ship through the air, and is usually present in a very small proportion when related to total resistance. Ships that are usually large in size and having super structure are naturally possessed with high air resistance than others, which are highly exposed to air (Theotokatos, and Tzelepis, 2015).

Other than the total resistance depending on the displacement variations and fouling state, it is also depending on the depth of water and sea state. Strong winds, big waves, and currents are also sources of increasing resistance (Theotokatos, and Tzelepis, 2015). For example during the head-on navigation, sea will extremely increase the resistance as compared to calm weather conditions. Shallow waters carry the effect that displaced water present underneath the ship will face more difficulty in moving forwards and creating higher residual resistance. The recommendation in this case is to use the phenomenon of sea margin, which means leaving a margin in the engine power in case of increased resistance during bad weather.

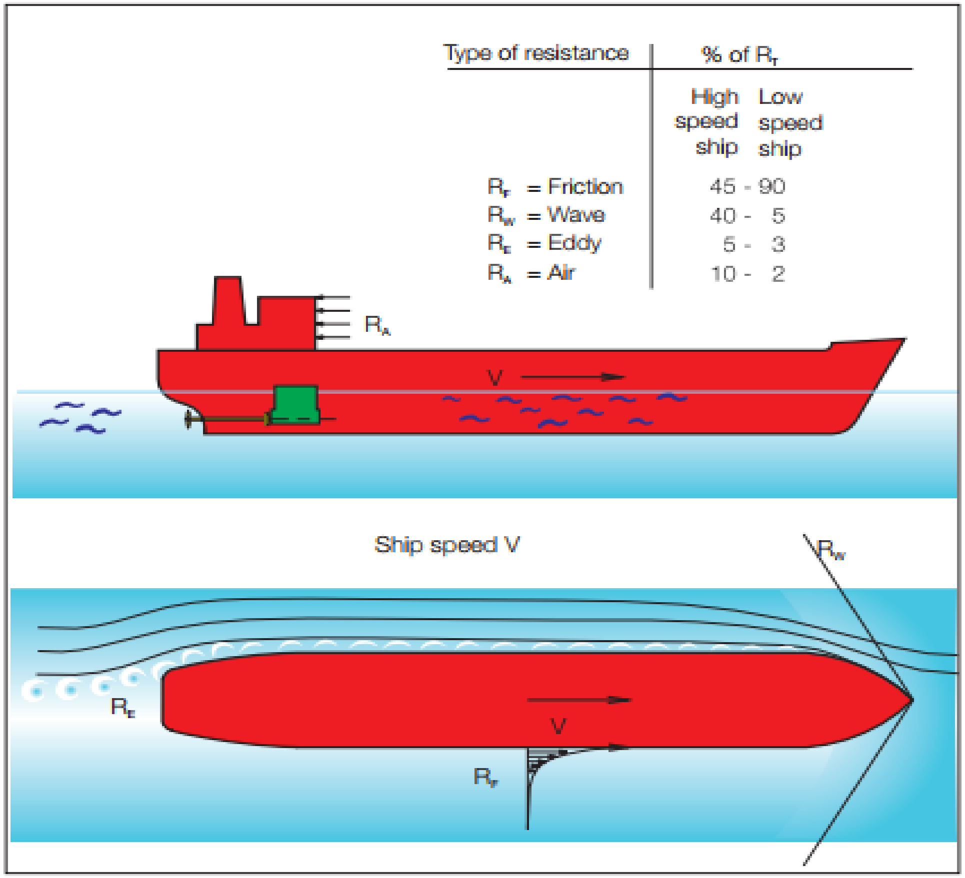

Figure 2.1 Different types of resistances

2.2.2 Propeller Propulsion:

The principle on which the propeller is working is to translate the rotational power gained from the engine to the thrust in moving the ship forward. Conventionally, the thrust of the propeller and torque characteristics found from performing tests in water tanks. Due to the fitting of the propeller on the stern of the ship, the performance influenced by the variations of water conditions generated by weather conditions and hull resistance (Zhang, et.al, 2014).

Propeller pitch:

There are two types of the pitch propeller; the fixed pitch propeller (FPP) or Controllable pitch propeller (CPP). FPP is the fixed orientation of the propeller blades, whereas the CPP is the hydraulic control of the pitch blades. Shown is figure2.2, the pitch of the propeller explained as the distance traveled per revolution when the propeller advanced as a screw with the angle of screw equal to blade angle (Zhang, et.al, 2014).

Interaction of hull and propeller:

When the propeller installed on the hull of the ship, it will deviate the characteristics of the propeller from its characteristics of open water. When the ship moves through friction of water then hull will drag the water along with the motion of the ship. This term of forward-water moving called wake. The wake velocity acts in the same direction of the ship. The wakefield is always dependent on the hull form; therefore, the same propeller will give different performance on individual ships. The wakefield also increased with the fouling of the hull because the surface of the hull gets rougher resulting in less homogeneous flow field (Kawamura, Ouchi, and Nojiri, 2012).

Thrust losses:

The ideal condition for a propeller is when it deeply flooded in calm waters. The losses that are affecting the propeller wake includes thrusters-hull interaction and transverse water inflow. In-line velocity fluctuations occur due to vessel motion, waves and currents creates a time-varying velocity across the propeller leading also to thrust losses. The best propeller speed is dependent on the number of blades and the diameter of the propeller (Kawamura, Ouchi, and Nojiri, 2012).

Ventilation can occur when the load to propeller exceeds and due to high waves, also low pressure on the propeller causes the air to tense from the free surface that creates a less optimal environment for the propeller. A propeller full-ventilated cause lose approximately 70-80% of its torque and thrust (Altosole, et.al, 2012).

Slip:

The slip used for finding out the load presented on the propeller as illustrated in the figure 2.2 below. If the propeller is operating in the unyielding medium like the screw in a wall then the forward velocity of the propeller will be the product of geometric pitch and angular velocity. When the propeller is heavily loaded and sailing against waves or winds, with a fouled hull, in shallow water and heavy loaded ship or when accelerating, then increment in slip will take place (Ji, et.al, 2010).

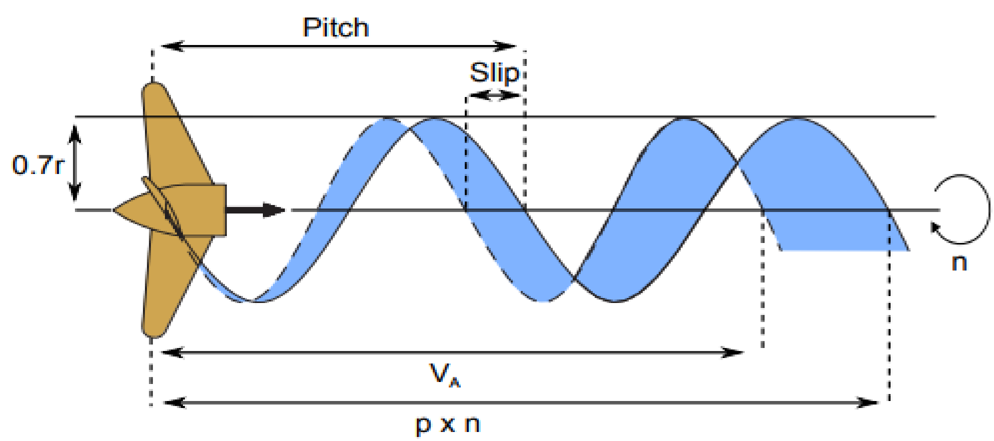

Figure 2.2 Illustration of propeller slip (ji, et.al, 2010)

2.3 Engine Layout:

Referring to Figure 2.3, which presents the engine layout diagram highlighting the operating regions of the engine. The propeller design point (PD) is the combination of speed and power of the engine that is appropriate for the projected ship. The design point is indicated on light running propeller curve that is representing the ship in good weather and clean hull (Song, Song, and Gu, 2015). For the bad weather, an alternative design is used.

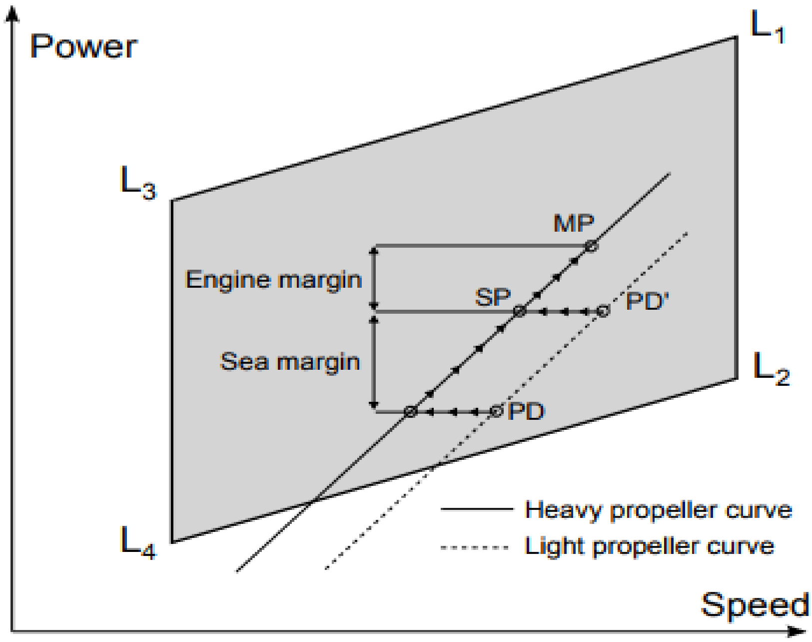

Figure 2.3 Ship engine layout (Song, Song and Gu, 2015)

When there is additional resistance in the form of bad weather, then fouling of the hull resistance with time will result in a heavier propeller curve. Due to this reason, an extra engine margin added in addition to sea margin.

2.4 Engine load:

The load of the engine is dependent on different components and factors that illustrated in figure 2.4 in which the curves of different factors highlighted with their specific values. The engine load diagram highlights the speed and power limits as well as the overloaded operation of the engine. The electronic governors used in the diesel engine protect the engine from mechanical and thermal overload because they include the scavenge air pressure limiter and a torque limiter. The air pressure limiter insure that the cylinders are receiving enough air during the acceleration for the perfect combustion. This will help in limiting the fuel administration if the air pressure is very low. To avoid engine mechanical overload then the fuel injection limitation is there according to the current engine speed and it is done by limiting the torque. The torque limiter is also shown in the image below but scavenge limiter is not illustrated in the figure (Song, Song, and Gu, 2015).

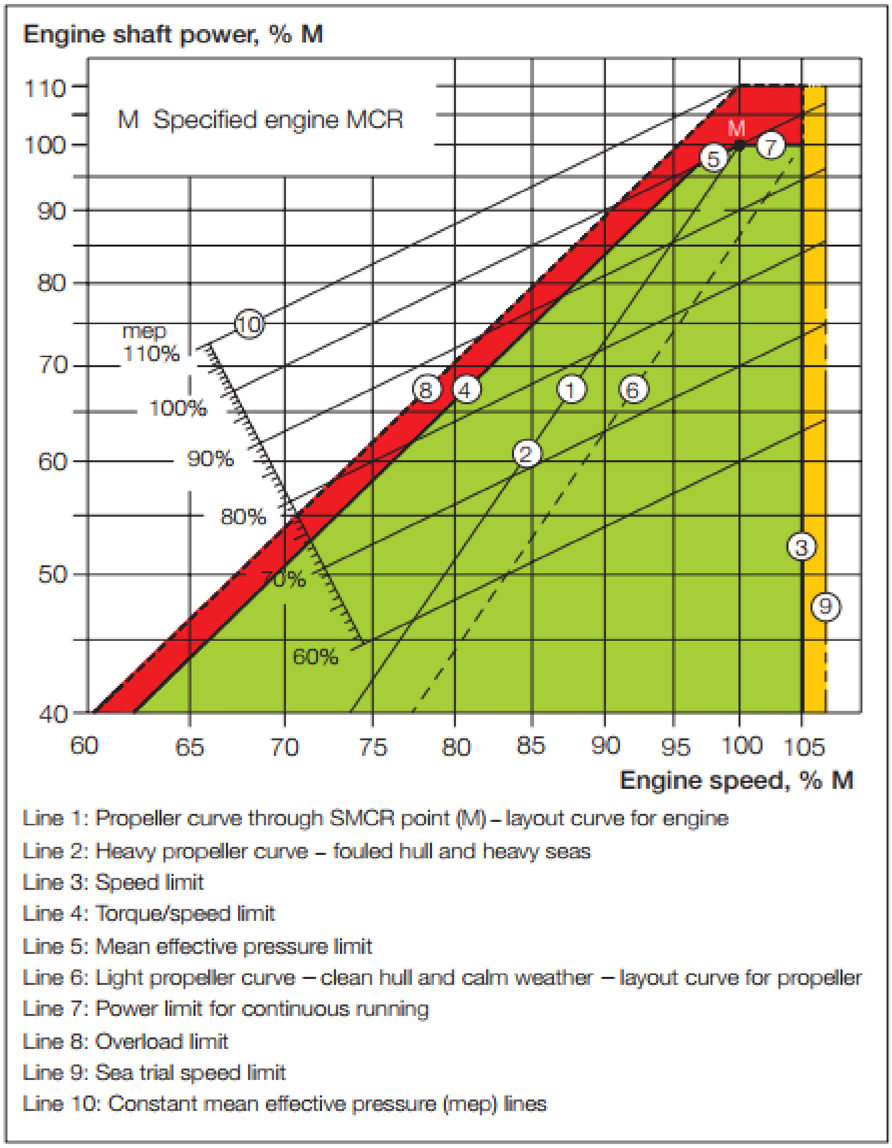

Figure 2.4 Engine load diagram (Song, Song and Gu, 2015)

2.5 Turbocharger maps:

A turbocharger consists of a turbine and a compressor connected to the common shaft. The task of the compressor is to lead the air from outside of the engine to the intake manifold, increasing the pressure and density at the same time. Increased air density in the cylinder means that more oxygen can now fit in limited space cylinder hence leading to burning of fuel efficiently (Wu, et.al, 2006).

In the same research, the turbine explained as a component that presents between the exhaust manifold and outside of the engine. The gas energy from exhaust provides power to the turbine by making the common shaft rotate. The faster the turbocharger rotates more air is drawn into the compressor. The performance of the turbocharger usually described by the manufacturer of the turbocharger.

2.6 Compressor map modeling:

Turbocharger failed in some of the projects due to the mapping design of the compressor and this section will explain this map in the engine. The compressor map is generated on the rig test results. The physical process in turbocharger is complex and obtaining perfect models is difficult or sometimes even impossible. The research indicates that a precise model is sometimes too complex to evaluate efficiently as calculation of some parameters are very difficult to find out. Interruption methods then used for estimating the unknown regions and another option is to make simple functional relationships through the observation of connections between the variables and general guidelines (Wu, et.al, 2006).

2.7 Diesel-electric propulsion system:

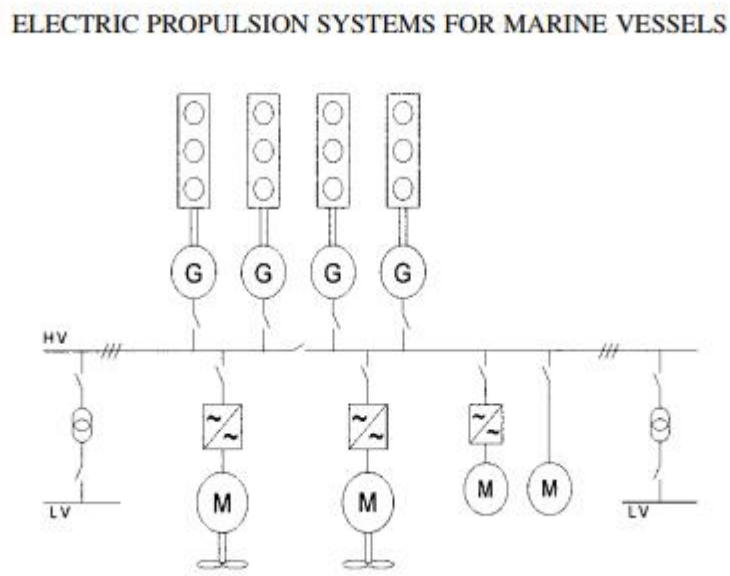

Figure 2.5 Diesel-electric propulsion system (Hansen, Ådnanes, and Fossen, (2001))

The figure above is indicating the general components of the propulsion system. Diesel-generators are usually present in the marine for the purpose of power production except for some places where gas turbine is used. The generator acts as a supplier and supplies the busbar with active power (P) and reactive power (Q). This busbar divided into two or more sections for ensuring redundancy. The level of voltage varies with the installed power and typically, 11Kv given to install 20MW power. The high voltage helps in keeping short circuit and load current low (Hansen, Ådnanes, and Fossen, (2001)).

The main power consumers in marine are usually the thrust drivers and propulsion that consist of different types. The propellers will be either variable or fixed pitch. The reason for using synchronous and asynchronous motors is for propulsion and the motors used are the highest power ratings. For the ships like ferries or cruise-liners the synchronous motors used due to the presence of several small thrusters. Pulse width modulation converters, cycloconverters or load-commutated inverters (LCI) are the most commonly used converters in the thrusters-drivers. Theoretically, all the combinations of propulsion motors, propellers and converters may be used but the most common thrust drivers used today are PWM converters that are asynchronous motors and LCI or cycle-converters used with synchronous motors (Hansen, Ådnanes, and Fossen, (2001)).

2.7.1 Advantages and disadvantages of Diesel-Electric Propulsion System:

Starting with the advantages of the system, the first and most important advantage is the reduction of fuel consumption. By running the specified numbers of diesel generators for every load condition at optimum, results show reduction of overall fuel consumption as compared to conventional diesel connection, even considering the losses due to additional electrical link. Another advantage is due to the presence of electrical propulsion, two or more power buses are used which allows the power availability in case of a fault. In addition, by using the azimuth thruster / podded propulsion, the manoeuvrability of the vessel resulting improvement in fast responses of stopping and turning movements, etc. In terms of engine room, arrangement higher flexibility achieved because electrical propulsion system takes very less space and the diesel generator placed on a suited place, this result in noise reduction and engine room can be used for influencing the ship stability. The electrical motor is also far more silent than the diesel engine with same rated power. Due to the optimal running of a diesel engine, the maintenance need is also decreased (Hansen, Ådnanes, and Fossen, (2001)).

The disadvantages of the Diesel-Electric Propulsion Systems are more components resulting in higher investment cost, additional losses during full-load operations and other training requirements for maintenance and operations department personnel.

2.8 Modelling specifications:

A power management system (PMS) responsible for controlling the operation of the Diesel-Electric Propulsion Systems. It is responsible of selecting the number of needed generators to be run during the operation, depending on the load demand from pumps, thrusters, and other loads. For example, the availability of the power is checked by the PMS for starting of large loads and then decides whether another diesel generator is needed to be started or not. Smaller load changes carried by making sure there is always reserve power present according to safety limits. The modeling specifications according to the research of Hansen, Ådnanes, and Fossen, (2001) are:

- A General mathematical calculation highlighting the number of components as generators and thrust drivers. Other consumers represented with the aggregate load.
- On/off feature for the thrust drivers and generators to simulate component outages.
- PMS usage for focussing on power production hence dynamic models used for generators whereas simplified static models used for thrust drivers.

2.9 Overall model structure of power generation:

The power generation consist of synchronous generators that are powered by medium speed diesel engines supplying the power to a common load, PID controllers and low-level speed controllers. In the stiff networks, an infinite busbar with fixed frequency and voltages used as the reference for the power angle and busbar voltage. Also, it is important to know that the power system of the marine is an isolated system and the calculation of the model will depends on the generators rotor speed (Hansen, Ådnanes, and Fossen, (2001)).

2.10 Electric propulsion:

Electric propulsion is turning out to be an emerging area in which various competence areas meet. The concept of electric propulsion is not new and it originated more than 100 years ago. However, due to the possibility of controlling electrical motors in a large power range with compact, cost-competitive and reliable solutions, the use of electrical propulsion emerged in new applications during the 80s and 90s. The configuration of electric propulsion with gas turbine or diesel engine driven power generation now used in hundreds of ships present in various types and a large variety of configurations (Kanellos, Prousalidis, and Tsekouras, 2014).

The main advantages of electric propulsion systems are that, firstly it has improved life cycle due to reduced fuel consumption and maintenance, especially when there are large variations in load demand. Secondly, Vulnerability also reduced due to a single failure in the system to the possibility of optimizing the prime movers (gas turbine or diesel engine).In addition, easily controllable speed of the diesel engine due to different modes. Finally, the flexibility achieved in locating thruster devices because thruster supplied with power through cables and can be located very independently.

The main difference between a land-based and marine electrical power system according to the research of Lamden (2012) is the fact that marine propulsion system considered as an isolated system having the shorter distances between the generated power and the consumers. In contrast, we all know that distances in land base electric system whereas the distances between the consumers and power generation can be smaller or they may be thousands of km. According to Yaxin and Yaxu (2012) the propulsion system of the ship is simpler than land-based system but on the contrary article of Geertsma et.al, (2017) has argued that electric propulsion system of the ship needs more control which is not easy to gain and this acts as the special challenge for the engineers for getting more control over it. During to the technology studies done for improvement and advancements in increasing the capabilities of microprocessors, computers and communication networks it has become easier to integrate the system and control it.

2.10.1 Power flow and efficiency:

Due to an isolated system, the amount of power generated must be equal or greater than the consumed power including the losses. An electric system illustrated in figure 2.6 highlighting the power flow of the system:

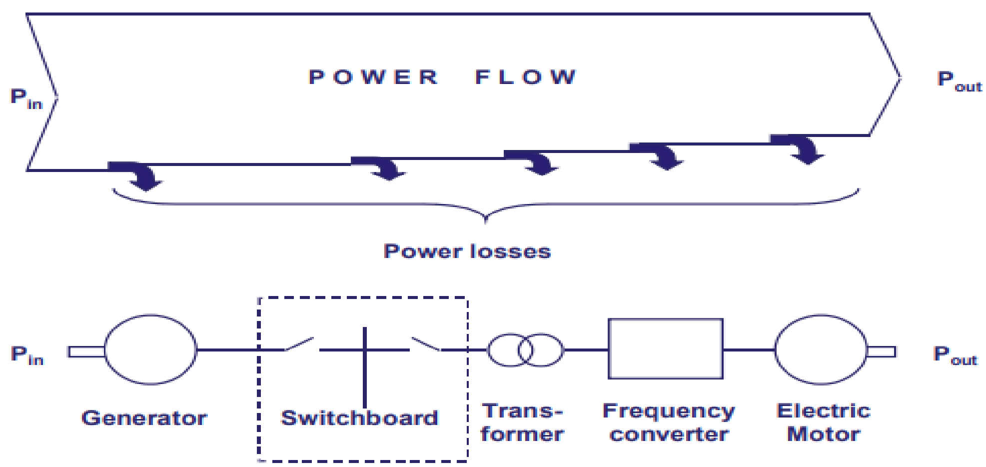

Figure 2.6 Power flow in simple electric power system

The prime suppliers that are gas turbine or diesel engine supply the power to electric generator shaft. The electric motor that is the propulsion motor is loaded with power from its connected load. The power loss that occurs in the components between the shaft of the diesel engine and the shaft of the motor is mechanical and electrical losses, which results in increasing the equipment temperature. The efficiency of the system is calculated by finding the ratio of the output power to input power (Hansen, Ådnanes, and Fossen, 2001). The efficiencies of each component found out to be:

- Generator = 0.95 – 0.97
- Switch board = 0.999
- Transformer = 0.99 – 0.995
- Frequency converter = 0.98 – 0.99
- Electric motor = 0.95 – 0.97

Hence, the efficiency of the diesel-electric system from the diesel engine shaft, to the electric propulsion motor shaft, normally found out to be between 0.88 and 0.92 at full load. The efficiency is strongly dependent on the loading of the system. The additional components between the propeller shaft and prime mover are contributing to 10% of the approximate losses hence the fuel saving factor is not due to the electrical component. The hydrodynamic losses vary significantly as they are dependent on the operational conditions for a CPP used in direct driven solutions of diesel compared to variable speed fixed pitch propellers (FPP), which are used in electric propulsion systems (Fletcher, et.al, 2010).

In most of the CPP conditions, to keep the speed of the propeller constant then the rotations should be high even though when the thrust demand is zero. Whereas for the FPP, the variable speed drive will allow zero RPM at the demand of zero thrust. The advantage of using CPP is that the pitch ratio of the propeller is hydro-dynamically optimized for higher speed range. The propeller designed for high transit speed will reduce the efficiency while working at low speed and vice versa. Hence, the operational profile is important to take place during the designing of the propulsion system (Fletcher, et.al, 2010).

The fuel efficiency characteristic of a diesel engine with maximum fuel efficiency in the load range of 60 to 100%, is strongly contributed to the differences in power consumption for a traditional propulsion system and diesel propulsion system. The power plant of diesel-electric propulsion consists of smaller diesel engines, where the number of running aggregates can be selected for having an optimum loading of each engine. The rating of the engine available can also be adopted for fitting in the intended operational profile of the vessel, by ensuring that there is a possibility of finding the optimal solution for most of the operational modes and time (Fletcher, et.al, 2010).

2.11 Historical overview of electric propulsion:

After the experimental application of battery-driven electric propulsion system which took place at the end of 19th century in Russia and Germany, the first generation electric propulsion used in 1920's due to the result of strong competition for reducing transatlantic crossing times for passengers lines. At that time, the high demand of the power in propulsion achieved by turbo-electric machinery where "S/S Normandie" was the most renowned. Steam turbine generators used for providing the power to drive the 29MW synchronous electrical motors present on each of the 4 screw shafts. The rotations are provided by the electrical frequency of the generators. The generators normally used for running one propulsion each, but there was a possibility of feeding two propulsion motors from each generator for cruising at lower speeds (Dimopoulos, et.al, 2014).

As indicated in the article of Doerry et.al (2015) when highly efficient and economical diesel engines introduced in the 20th century market in the middle, the electric propulsion and steam turbine technology were more or less disappeared from the market until 1980.

However, when the development of AC / AC converters in the 1980s and the AC / DC rectifier in 1970s took place it then played the role as a revival of the electric propulsion system and is regarded as the second generation of the electric propulsion system (Rajashekara, 2013). The research of Doerry et.al (2015) has also argued that this electric propulsion system operated on a fixed frequency and voltage power plant that consists of a huge number of generators where supplying power to the system as well as auxiliary and hotel power. This propulsion indicated in the research of Rajashekara (2013), is done by controlling the speed of the fixed pitch propeller. These electric propulsion systems were early used in special vessels such as icebreakers and survey ships and later on in cruise vessels (Dimopoulos, et.al, 2014; Doerry et.al, 2015). When these systems shows appropriate and reliable results than they were implemented on some of the ships at that time because the old propulsion systems replaced by the electric propulsion system. The main difference between the diesel propulsion system and electric propulsion according to De Santiago et.al, (2012) studies is that in diesel propulsion system thrust normally controlled by using a hydraulic system and varying the pitch angle. This term often denoted as controllable pitch propeller (CPP).

After the development of electric propulsion system another propulsion system namely podded propulsion system was introduced in the early 1990s and according to Rajashekara (2013), this propulsion system electric motor is directly installed on the shaft of fixed pitch propeller in a submerged and rotatable pod. Doerry et.al (2015) has argued that this system was developed for enhancing the performance of icebreakers but later it was used in many other platforms due to its additional benefits of hydrodynamic manoeuvrability and efficiency. The research of Dimopoulos (2014) also explained that when this propulsion system was installed in “M/S Elation”, a cruise liner, then the advantages gained were so much convincing that podded propulsion over nightly became a standard of the new cruise liners. An example of podded propulsion system depicted in the figure below:

Figure 2.7. "M/S Elation" a Cruise vessel consisting of Azipod propulsion on lower right (Dimopoulos, 2014)

2.11.1 Electric propulsion system in cruise ships and ferries:

Cruise ships, ferries, and passenger's vessels are considered as one of the most critical sources of traveling in which the requirements for the onboard comfort level are very high (Skjong, et.al, 2015). Furthermore, the availability and reliability considered as a critical component for the safety of the vessels and passengers. Consequently, it was earlier believed that electric propulsion system beneficial and was mostly used (Dimopoulos, et.al, 2014; Rajashekara, 2013).

The ships that are consisting of electric propulsion system today is long and increasing in sizes. Since the podded propulsion found out to be having significant impacts on fuel costs and manoeuvrability, which increases the efficiency up to 10% (Doerry, et.al, 2015), a large and further increasing numbers of new ships pre-installed with electrical podded propulsion.

Since the concerns about the environment are increasing the requirements for the reduction of damages, spills and emissions are also increasing (Yutao, et.al, 2012). Hence it is necessary as suggested in the research of De Santiago et.al (2012) that vessel must try to maintain its position only by thrusters that are controlled by a DP system because it will increase the need of podded and electric propulsion even more in the market.

The research of Rajashekara (2013) has also indicate that with the passage of time environmental concerns is also increasing for this reason the increment need to be controlled. Furthermore, similar cases with gas emissions (Nox, Cox and SOx) which will also increase with the passage of time due to the increment numbers of ferryboats installed with the electric propulsion system. The research of Skjong et.al (2015) also agrees with the statement that said 'due to increased and frequent quay docking and crossing schedules, the manoeuvrability that was improved earlier in podded propulsion is getting affected by the reduction of the fuel consumption'. The power of propulsion system always varies according to the size of the vessel. In small ferries, the difference is in few megawatts whereas in large cruise liners the difference is between 30-40 MW (Doerry et.al, 2015). The load of the hotel in large cruise ships is a major contributor in energy consumption typically consuming 10-15MW of energy.

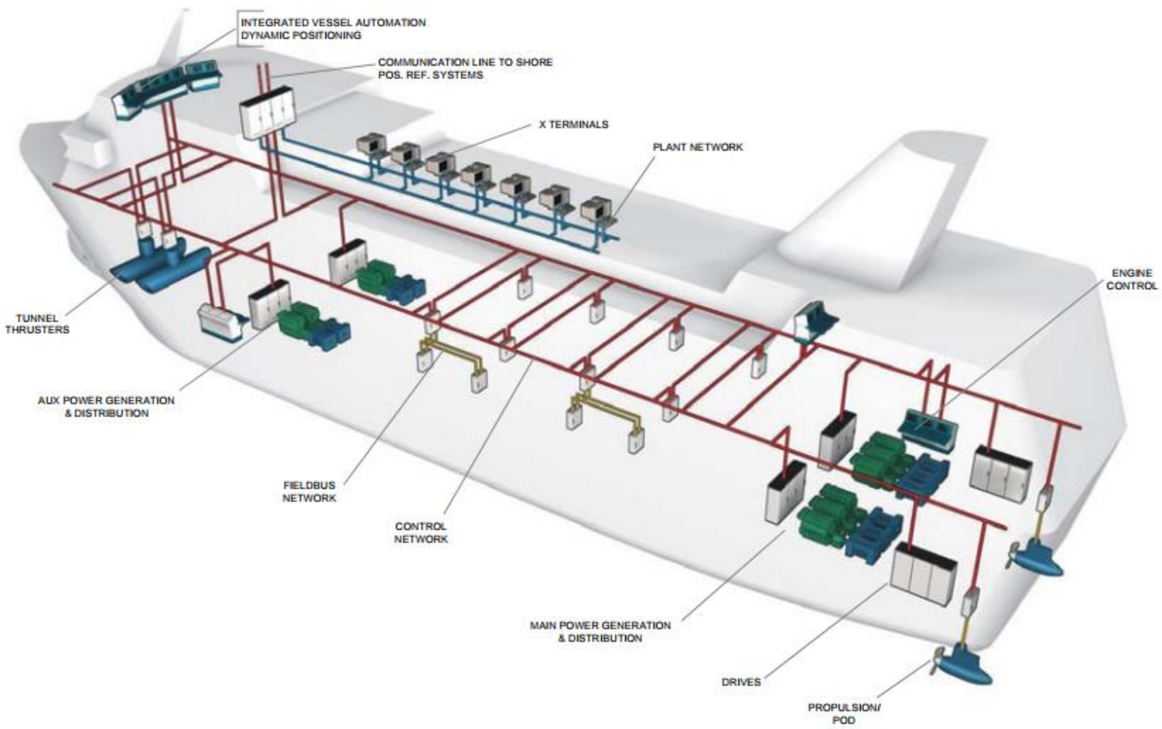

Figure 2.8 an example of control and propulsion system layout in a cruise vessel (Doerry, et.al, 2015)

2.11.2 Electric propulsion system in War Ships:

The research of Dimopoulos et.al (2014) and Doerry et.al (2015) argued that although great interest has been shown in electric propulsion system in war ships, currently there are less than expected number of ships that are having pure electric propulsion, but some of them are being projected. Similarly, in submarines the propulsion system that is installed consists of a diesel engine, fuel cell, and battery storage is applied, alternatively in some cases nuclear power plant is applied also (De Satiago, et.al, 2015).

2.11.3 New applications and trends:

The electric propulsion system continuously evaluated and investigated for the new applications. Some of the examples that have been collected by studying the literatures are Ro-Ro vessels, LNG, and chemical tankers, fishing vessels and container vessels are examples of big markets where electric propulsion is not installed yet because of the drawback of costly investment (Bo, et.al, 2016; Geertsma, et.al, 2017; Lamden, 2012).

2.12 Power distribution in propulsion system:

The power generation in marine propulsion system done using many components such as switchboards, Transformers, and generators.

2.12.1 Switchboards:

Switchboards that are installed with the generator or anywhere else are usually distributed in 2, 3, or 4 sections in order to make them easily reachable in case of emergency switch off needed (Doerry, et.al, 2015). Furthermore, these switches also act in obtaining the redundancy requirements of the vessel. According to the rules and regulations that have been set for the propulsion system if one of the switchboard section fails than the other one will control it. In other cases such as flooding or fire, there is special technique as indicated in the research of Lamden (2012) that waterproof and fireproof dividers installed in the switchboards will bear all the consequences.

When the two-split configuration used in the load of the generator equally divided than maximum single failure scenario will lose 50% capacity of the generator on the loads. The research of Bo et.al, (2016) and Geertsma et.al (2017) suggested that for avoiding the high installation cost, the system usually split down into three or four sections, which acts in reducing the required installation costs as well as the space. According to Yaxin and Yaxu (2012) in the propulsion mode, the switches normally connected together, which results in achieving best flexibility in the configuration of power generation plant. Furthermore, the transients load become easier to be distributed on large numbers of diesel generators resulting in most optimal numbers of units that can be joined in the network (Skjong, et.al, 2015).

Another alternative configuration that has been indicated in the research of El-Gohary (2012) and supported by Kobougias et.al (2013) is to do sailing with the independent parts of switchboard that are supplying the power to two or more independent networks. If this configuration adopted than ship considered virtually blackout-proof and it could look attracting in congested networks. When the ship is operating on this mode of propulsion, there is a drawback shown in the research of Rajashekara (2013) which said that if there is a loss in one of the networks that are connected to one of the propulsion units, than the switchboard that is connected to that section also will stop working completely. However, other networks will remain working because of connected separately. Hence, that research has also suggested to keep the important units independent such as the cooling units, lubrication, and ventilation system must be installed on the reliable network.

The article of Theotokatos and Livanos (2013) has given some important information. According to them as the installed power in the propulsion system increases, then short-circuit current and normal load current also increases resulting in increased chances of failure. Due to physical limitations of handling the propulsion system, it becomes necessary and advantageous to increase the voltage of the system resulting in the reduction of current levels. Bo and his partners (2016) argue that most of the propulsion systems are operating on medium voltages because it has become necessary due to increasing demand of power in many applications.

Circuit breakers normally used for connecting and disconnecting load units or generators to different parts of switchboards together (El-Gohary, 2012). In today's world, different types of circuit breakers having various technologies are easily available. Although air insulation units are one of the traditional solutions, they are rarely used today except for the requirements where low voltage levels are required. One of the most commonly used circuit breaker according to the findings of Yaxin and Yaxu (2012) is the SF6 and vacuum breaker technology. In this, the interruption of current takes place in the enclosed chamber, in which the first one filled with gas labeled as SF6 and that gas has higher strength of insulation and hence vacuum breaker is needed to be evacuated by air. This design considered as compact and having long-term reliability solutions for the ship that is operating on the medium voltages. It is important to note that vacuum breakers may chop the current and also cause spikes on overvoltage which will lead in reducing it by installing the overvoltage limiters (Kobougias, et.al, 2013).

For the ships operating on small voltages where fused contactors used that are cheap and also space beneficial alternative for the circuit breakers and according to Lamden (2012) they are also available in low voltages such as SF6 or vacuum insulated types. The problem associated with the switching spikes becomes immensely less with the fused contactors because on low voltages the interruption of current is also softer.

2.12.2 Transformers:

The transformers also play an important and a comprehensive role in the power distribution of marine propulsion system. The main purpose of the transformer in marine propulsion system explained in different researches. According to Dimopoulous et.al (2014), the main purpose for which the transformer used is to do isolation of different parts of electric power distribution into several different partitions for obtaining different levels of voltage and sometimes for phase shift as well. One of the advantages of phase shift transformers is that they can be used for feeding frequency converters, e.g. for controlling variable speed propulsion drives and for reducing the injection of distorted currents that is travelling in the electric power network, this is done by cancellation of most dominant harmonic currents (Armstrong, et.al, 2012). This statement supported by the research of Rzadki and Horn (2013) who have shown that by doing this the distortion in voltages of generators and other applications reduced. The transformer also produces a damping effect that is of high frequency, which emits a noise.

In the article of Spichartz, Staudt, and Steimel (2013), it states that there are different numerous and different types of transformers currently used in propulsion systems among and the most important and common types are: resin insulated, air insulated dry type, or oil insulated. Physically the transformer is built by using three phase units having three phase of primary coils and three phase of secondary coils (Yaxin and Yaxu, 2012). There are different configurations of transformers such as ‘Dy’ type transformer and ‘Dyn or Ynyn’.

2.12.3 Motor drives used in propulsion systems:

The electrical motor is one of the most common types of motor used in the marine propulsion system according to the research of Theotokatos, and Livanos (2013). In the electrical power of the ships, the need of converting it into mechanical power is important in order to use the electric propulsion, station keeping or thrusters for propulsion and for other onboard loads such as pumps, winches, fans, etc. The article of Yutao et.al (2012) also argues that typically 80-90% of the load that is running on the ship is of the electrical motors. In this section of the report, arguments presented based on different types of motors, and how they are playing parts in the propulsion system of the ship. The factors focussed in presenting the arguments are design, characteristics, and performance by referencing the research articles and books.

DC motors: In the marine propulsion system and also in other areas DC motor always operates on the DC supply, and since the distribution system and power generation normally operates on the three-phase system (Spichartz, Staudt, and Steimel, 2013), it means that this moto supplies the power from the thyristor rectifier. This results in the speed control of DC motor (De Santiago, et.al, 2012).

Asynchronous motors (induction motors): this motor is also popular for its use in marine propulsion system according to the findings of Lamden (2012) because of its rugged design which ensures that it will perform well for a longer period of time and also have very little requirement of maintenance (Karlsen, 2012). This motor mostly used where the requirement is of constant speed because of the ability of directly connecting it to the network or fed from the static frequency converter.

Synchronous motors: This motor normally recommended for using it in the ship propulsion system. It is only used where propulsion drives are operating at the power greater than 5MW and are directly connected to the propeller shaft with the gear connection (El-Gohary, 2012; Geertsma et.al, 2017). In the environment where the requirement of power is smaller than this asynchronous motor found out to be cost-competitive. Both the motors are having similar designs (Bo, et.al, 2016) but the synchronous motor is not operated without the frequency converter because in ship variable speed control is required that can only be achieved by a frequency converter.

Permanent magnet synchronous motors: These motors normally used in the industrial drives where the requirement is of few KW drives and sometimes for direct online-applications (Armstrong, et.al 2012; Doerry, et.al, 2015). In recent years, some of these motors used in the areas of large power; in different types of propulsion drives such as in navy applications (Dimopoulos, et.al, 2014) and now in podded propulsion systems as well. The reason of using these motors in the ship propulsion system, because of its design that is highly efficient which makes it special for podded propulsion in which dimensions should be as small as possible (Rzadki and Horn, 2013). Furthermore, direct water-cooling will also eliminate the need of air-cooling of the pod motor by simplifying the installation and construction work (Skjong, et.al, 2015).

Other motors: There are wide variety of motors available for experimental or commercial applications. Few of them are able to survive in the market and very few of them in marine applications (Theotokatos, and Livanos, 2013). There is a possibility in the future that new concepts of variable speed drives will be developed resulting in failure of current motors and rise of the fallen one. In marine propulsion, the requirement of motor is that it should be high efficiency and must be small dimension and operating in a big number of applications (Rajashekara, 2013).

2.13 Controlling strategies of variable speed motor drives:

The motor that is widely used in the current period in propulsion system is direct online motor. This motor is directly being operated by network frequency and changing its speed accordingly (De Santiago, et.al, 2012). The research of Lamden (2012) has suggested that there may be low losses if the fuel consumption and power are saved for the pumps and winches. Furthermore, the controllability of the load that is driven greatly enhanced if the speed of the motor is controlled accurately. The article of Rajashekara (2013) argues that this target of perfect propulsion system will require additional investment costs and also the components that will be helpful in performing these tasks. The writer also indicates the price that is 1NOK per kWh for the generated power, and on the ship propulsion system, the requirement is of 8-9 MNOK annually for the 1MW average power reduction.

In ships, the mostly used sped drive is the one that uses AC motors (Yutao, et.al, 2012). Most of the drives except for cycloconverter, consists of a rectifier that is used for rectifying the line voltages and an inverter used for generating the variable frequency and a variable voltage source for the motor (Yaxin and Yaxu, 2012).

The motor controller is usually consisting of speed control and the control of the motor currents by controlling switching elements of the inverter and/or rectifier (Doerry, et.al, 2015). The research of Yutao et.al, (2012) has argued that there is a requirement of overriding control system, manoeuvring control, vessel management system and dynamic position control. The controller of the motor acquired the signals of the measurements and the feedback signals from the sensors and motors that are present in the drive (Skjong, et.al, 2015). Typically, the measurements of the motor current, speed and in some of the cases temperatures and voltages are also measured. The components presented in the power electronic circuits are either controllable or uncontrollable based on their characteristics.

The motors installed in the propulsion system of the marine can run in both directions. For deciding that in which quadrant motor should run it is necessary to categorize the conditions for which the motor is being designed. The research of Dimopoulos et.al, (2014) has indicated that for analyzing this quadrant of motor selection in which needed to be run. For example, if the motor is motoring which means it is running the load with power input to the load shaft in quadrants I and III and when the motor is operating in the II and IV quadrant than the mechanical power transferred from the load to the drive (Doerry, et.al, 2015). The motor drive as argued in the research of Lamden (2012) and El-Gohary (2012) is consisting of speed control function and the output from it can be interpreted as a reference or torque command, which is the input of the motor control algorithm. These algorithms more or less are using advanced model of motor for controlling the motor voltages and currents by turning the rectifier switches on or off and the inverter (De Santiago, et.al, 2012).

Based on the above-mentioned literature, the main aim of this dissertation is to make the system of marine propulsion as stable as possible and for that purpose, the calculations will depend on different methodologies that are linked with our aim and purpose of the research.

Chapter 3 – Research Methodology

The controllable marine propulsion system goes through several procedures and calculations before the stable controlled system. Starting with the knowledge of the propeller load behaviour where the propeller speed known in advance to calculate propeller load gains. To know the speed of the propeller in advance then the speed and shape of the ship should be clear and this will happen by studying the ship surge model. For these reasons, the chapter will start with modelling the propeller, followed by development of a simple ship surge model, and finally, adding lacked engine model from previous work such as shaft friction and overload control.

3.1 Mathematical Model

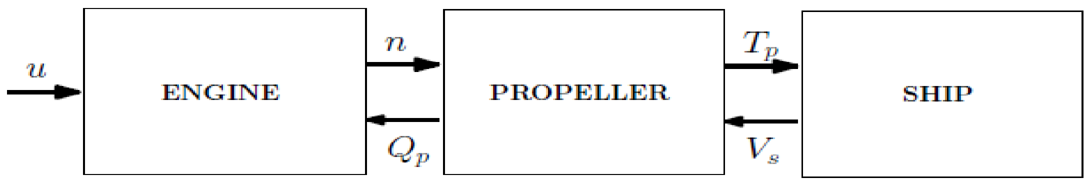

Figure 3.1 sub models communication block diagram

Shown in the above figure, the communication between the sub models in the marine propulsion system. As the calculation of the engine states taken from the fuel index (u) and the output is the propeller speed revolution(n). The value of the speed revolution used in calculating the load torque(Q_p), Also result in the output calculation of the propeller thrust (T_p). From the propeller output, the velocity is calculated and the recalculation of the engine speed depends on both propeller torque and thrust.

From the mechanical model:

$$T_1 = (J_1 s^2 + C_1 s + K_1)\theta_1 - K_2\theta_2 \qquad \ldots 3.1$$

$$T_2 = (J_2 s^2 + C_2 s + K_2 + K_1)\theta_2 - K_2\theta_3 - K_1\theta_1 \qquad \ldots 3.2$$

$$K_2(\theta_2 - \theta_3) = (J_L s^2 + C_3 s)\theta_3 \Rightarrow \theta_3 = \frac{K_2\theta_2}{J_L s^2 + C_3 s + K_2} \qquad \ldots 3.3$$

The equation for T_2 can be rewritten as:

$$T_2 = (J_2 s^2 + C_2 s + K_2 + K_1)\theta_2 - K_2 \frac{K_2\theta_2}{J_L s^2 + C_3 s + K_2} - K_1\theta_1$$

$$T_2 = \frac{J_2 J_L s^4 + (J_2 C_3 + J_L C_2)s^3 + (J_2 K_2 + C_2 C_3 + (K_1 + K_2)J_L)s^2 + (C_2 K_2 + (K_1 + K_2)C_3)s + K_1 K_2}{J_L s^2 + C_3 s + K_2} - K_1\theta_1 \qquad \ldots 3.4$$

The interface of the electrical and the mechanical model:

$$T_1 = \frac{K_{f1} V_1}{L_1 s + R_1} \qquad \ldots 3.5$$

$$T_1 = \frac{K_{f2} V_2}{L_2 s + R_2} \qquad \ldots 3.6$$

With the input as V_1 and V_2 and the output as θ_1 and θ_2, the system transfer for the 2×2 system becomes:

$$\mathbf{G}(\mathbf{s}) = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix}$$

With:

$$g_{11}(s) = \frac{K_{f1}}{(J_1 s^2 + C_1 s + K_1)(L_1 s + R_1)} \qquad \ldots 3.7$$

$$g_{12}(s) = -\frac{K_{f1}}{K_2(L_1 s+R_1)} \quad \ldots 3.8$$

$$g_{21}(s) = -\frac{K_{f2}}{K_1(L_2 s+R_2)} \quad \ldots 3.9$$

$$g_{22}(s) = \frac{J_L s^2+C_3 s+K_2}{J_2 J_L s^4+(J_2 C_3+J_L C_2)s^3+(J_2 K_2+C_2 C_3+(K_1+K_2)J_L)s^2+(C_2 K_2+(K_1+K_2)C_3)s+K_1 K_2} \times \frac{K_{f2}}{(L_2 s+R_2)} \quad \ldots 3.10$$

Therefore:

$$\begin{bmatrix}\theta_1(s)\\ \theta_2(s)\end{bmatrix} = \begin{bmatrix} g_{11}(s) & g_{12}(s)\\ g_{21}(s) & g_{22}(s)\end{bmatrix}\begin{bmatrix}V_1(s)\\ V_2(s)\end{bmatrix}$$

Upon substituting the values in Table 1 and Table 2 for the parameters, the MIMO system is represented as:

$$\mathbf{G}(s) = \begin{bmatrix} \frac{1.1494}{(s+0.9429)(s+0.195)(s+0.1758)} & -\frac{11.11}{(s+0.1758)} \\ -\frac{6.25}{(s+0.195)} & \frac{2.7778\,(s^2+0.109s+0.05769)}{(s+2.687)(s+0.195)(s+0.1758)(s^2+0.1909s+0.05428)} \end{bmatrix}$$

$\mathbf{G}(\mathbf{s})$ can be reduced using pole-zero cancellation to:

$$\mathbf{G}(s) = \begin{bmatrix} \frac{1.1494}{(s+0.9429)(s+0.195)(s+0.1758)} & -\frac{11.11}{(s+0.1758)} \\ -\frac{6.25}{(s+0.195)} & \frac{2.7778}{(s+2.687)(s+0.195)(s+0.1758)} \end{bmatrix} \quad \ldots 3.11$$

3.2 Open Loop Response Analysis and Control Objectives

To find the open loop response plot the parameters scaling are as following:

Table 1: Mechanical parameters

Parameter	J_1	C_1	K_1	J_2	C_2	K_2	J_L	C_3
Value	0.87	0.99	0.16	0.36	1.06	0.09	1.56	0.17

Table 2: Electrical parameters

Parameter	L_1	R_1	K_{f1}	L_2	R_2	K_{f2}
Value	1	0.1758	1	1	0.195	1

Further, g_{11} and g_{22} are modified into second order systems $\tilde{g}_{11}$ and $\tilde{g}_{22}$ by modifying their by removing from each the pole that is at least five times larger than the other two:

$$\tilde{g}_{11}(s) = \frac{1.2191}{(s+0.195)(s+0.1758)} \qquad \ldots 3.12$$

$$\tilde{g}_{22}(s) = \frac{1.0339}{(s+0.195)(s+0.1758)} \qquad \ldots 3.13$$

The resulting step responses due to the approximations are shown in Figure 3.2 and Figure 3.3 below. In both cases, the steady state remains the same in both systems. However, the reduced system is slightly faster in both cases.

The Nyquist diagrams of the original system and the reduced system are shown in Figure 3.4. In both cases, the system easily becomes unstable when the frequency is increased beyond a small lower threshold.

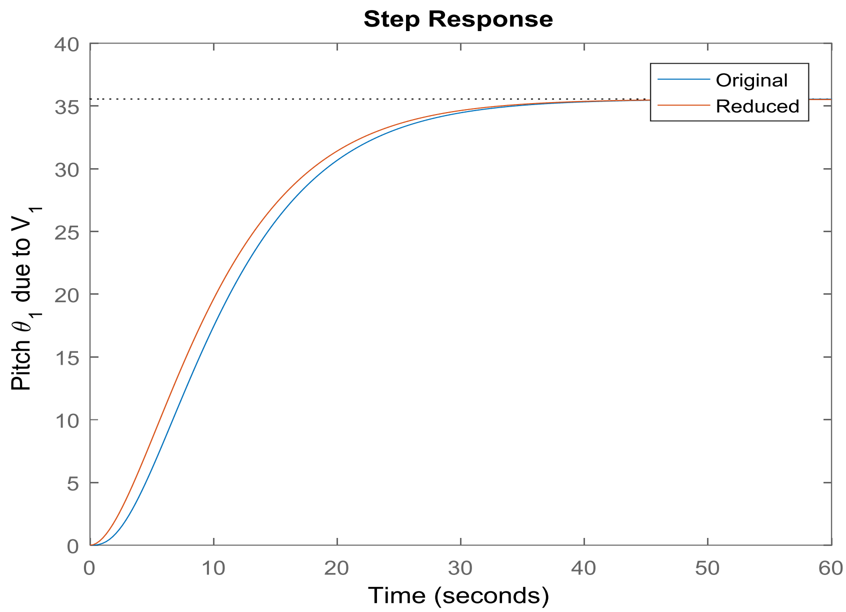

Figure 3.2 Original and reduced g_{11} step response

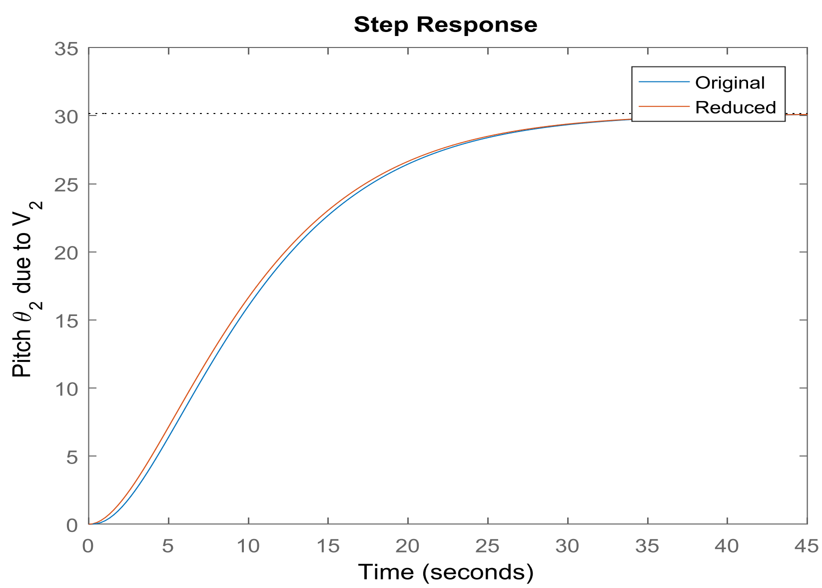

Figure 3.3 Original and reduced g_{22} step response

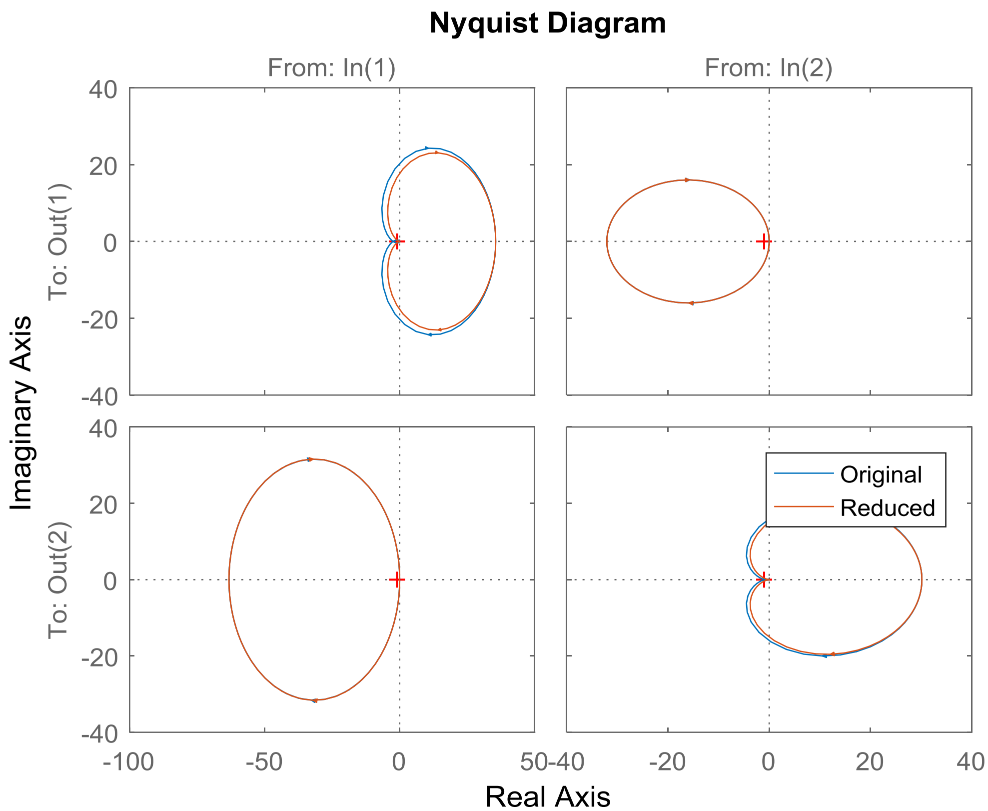

Figure 3.4 Nyquist diagrams of the original and reduced systems

The modified system transfer function then becomes:

$$\mathbf{G}(\mathrm{s}) = \begin{bmatrix} \frac{1.2191}{(s+0.195)(s+0.1758)} & -\frac{11.11}{(s+0.1758)} \\ -\frac{6.25}{(s+0.195)} & \frac{1.0339}{(s+0.195)(s+0.1758)} \end{bmatrix}$$

$$\mathbf{G}(\mathrm{s}) = \frac{\begin{bmatrix} 1.2191 & -11.11(s+0.195) \\ -6.25(s+0.1758) & 1.0339 \end{bmatrix}}{(s+0.195)(s+0.1758)} \qquad \ldots 3.14$$

The open loop model for the system was created in Simulink as shown in Appendix. The outputs obtained from the system are as shown in Figure 3.5 and Figure 3.6 below for $V_1 = 1, V_2 = 0$ and for $V_1 = 0, V_2 = 1$ respectively.

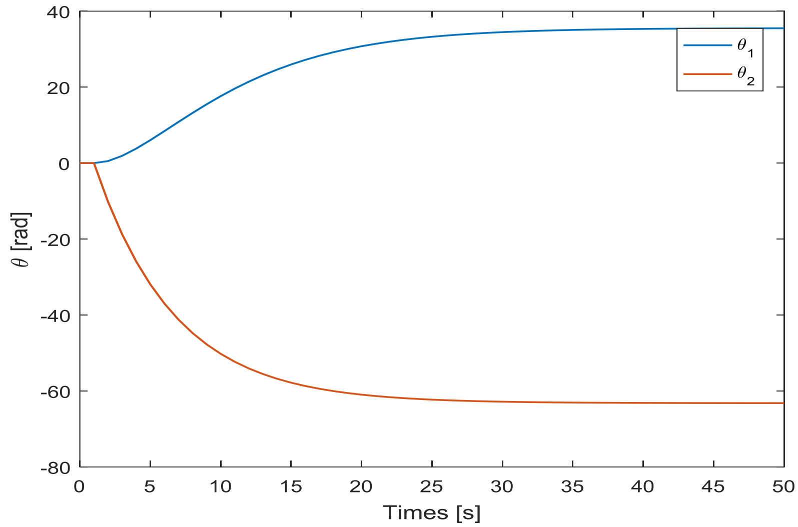

Figure 3.5 Output when $V_1 = 1, V_2 = 0$

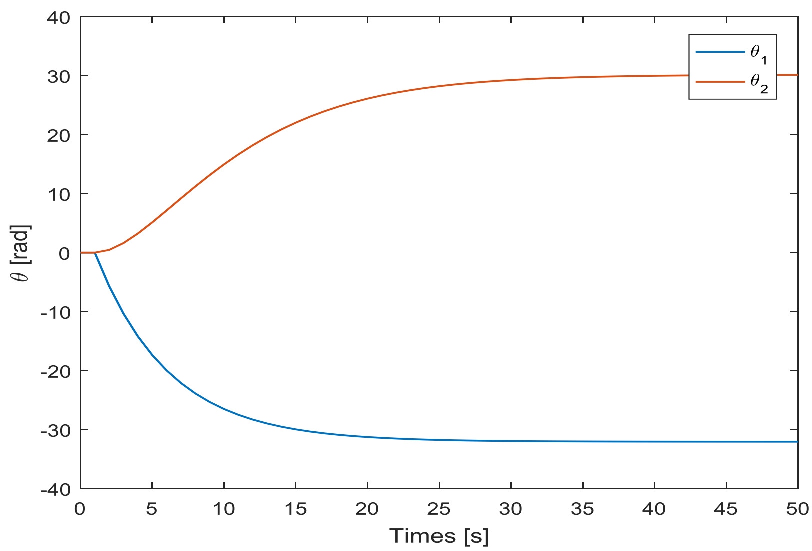

Figure 3.6 Output when $V_1 = 0, V_2 = 1$

3.3 Least Effort Control Method

In this method the design procedures are, a dual loop approach adopted where the inner loop is applied to insure acceptable stable dynamics, the outer loop and the pre-compensator are applied to satisfy output disturbances conditions. The derivation of formula is in accordance with Whalley and Ebrahimi (2006).

The open loop output equation in the Laplace Domain is:

$$y(s) = G(s)u(s) + \delta(s) \qquad \ldots 3.14$$

The closed loop control law for the proposed feedback is:

$$u(s) = k(s)[\acute{r}(s) - h(s)y(s)] + P\big(r(s) - Fy(s)\big) \qquad \ldots 3.15$$

In 3.14 and 3.15 equations are independent inputs, disturbances, and outputs, so:

$$F = Diag(f_1, f_2, \dots \dots \dots, f_m), 0 < f_j < 1, 1 \leq j \leq m$$

The inner loop controller is:

$$k(s)[\acute{r}(s) - h(s)y(s)]$$

Which is used to fulfil the specification of the dynamic behaviour of the closed loop system.

The outer loop controller is:

$$P\big(r(s) - Fy(s)\big)$$

Utilized to secure the required steady state interaction and disturbance recovery.

With $\acute{r}(s) = 0$, , the closed-loop equation becomes:

$$y(s) = \big(I_m + G(s)(k(s) >< h(s) + PF)\big)^{-1} \times \big(G(s)Pr(s) + \delta(s)\big) \qquad \ldots 3.16$$

Where in equation 3.16, $\|G(s)(k(s) >< h(s) + PF)\|_\infty$ finite for all on the D contour.

If the steady-state matrix is:

$$y(0) = S_s r(0)$$

In equation 3.16 when $s = 0$ then:

$$P = \left(G(0)^{-1} + k(0)\right) >< h(0)S_s(I - FS_s)^{-1} \qquad \ldots 3.17$$

For steady state, decoupling the matrix should be equal to the identity matrix($S_s = I_m$).

Usually, to achieve a low interaction, S_s would have diagonal elements of unity and off diagonal elements that are less than unity:

$$\left\|S_{i,j}\right\| \ll 1, \quad 1 \leq m, \quad i \neq j$$

Consequently, substituting $S_s = I_m \; instead \; of \; P$ from equation 3.17, the results in equation 3.16 will become:

$$y(s) = \Big(I_m + G(s)\big(k(s) >< h(s) + (G(0)^{-1} + k(s) >< h(s)(I_m - F)^{-1}F)\big)^{-1} \times$$

$$\big(G(s)Pr(s) + \delta(s)\big)\Big) \qquad \ldots 3.18$$

At low frequencies:

$$G(s)P \cong \frac{1}{1-f}\left(I_m + G(s)k(0) >< h(0)\right)$$

Therefore, equation 3.18 on steady-state conditions becomes:

$$y(s) = I_m r(s) + S(s)\delta(s) \qquad \ldots 3.19$$

Where the low frequency sensitivity matrix is:

$$S(s) = (1 - f)\left(I_m + G(s)k(s) >< h(s)\right)^{-1}, \; 0 < f < 1$$

The steady state is reached at this level and when the frequency increases because of any disturbances then the steady state disturbance rejection will also increase to insure system stability.

For implementing the regulator structure, there will be a forwards path $K(s)$ and a feedback path compensator $H(s)$, which is easily computed from equation 3.16.The input-output relation is:

$$y(s) = \left(I_m + G(s)K(s)H(s)\right)^{-1}[GK(s)r(s) + \delta(s)] \qquad \ldots 3.20$$

On comparing equations 3.16 and 3.20, evidently

$K(s) = P$ ...3.21

And

$K(s)H(s) = k(s) >< h(s) + PF$

Hence

$H(s) = P^{-1}k(s) >< h(s) + F$ ...3.22

Inner Loop Calculation: The design strategy to adjust the inner-loop $k(s)$ *and* $h(s)$ vectors to provide stable system with dynamic conditions. Thereafter, the pre-compensator is configured to produce acceptable steady-state output coupling, the outer-loop feedback gain becomes the ultimate design parameter enabling final dynamic and disturbance suppression characteristics to be achieved (Whalley and Ebrahimi ,2006).

Assume the open loop system $G(s)$ is linear, regular, proper, or strictly proper realization and admits a general factorization of:

$$G(s) = L(s)\frac{A(s)}{d(s)}R(s)\Gamma(s) \quad \text{...3.23}$$

Where $L(s)$, $A(s)$, $R(s)$, $\Gamma(s)$ and the elements of $\frac{A(s)}{d(s)} \epsilon H_\infty,\ s \epsilon \mathbb{C}$

In equation 3.23, $L(s)$ contains the left row factors of $G(s)$, $R(s)$ contains the right column factors, and $\Gamma(s)$ contains the transformed finite time delays then the matrices comprising equation 3.23 are:

$$L(s) = Diag\left(\frac{\lambda_i(s)}{p_j(s)}\right),\ \ R(s) = Diag\left(\frac{\rho_i(s)}{q_j(s)}\right)\ \ and\ \Gamma(s) = Diag\left(e^{-sTj}\right), \qquad 1 \leq i,j \leq m$$

Where $A(s) \neq 0,\ and$:

$$a_{ij}(s) = a_{ij}s^{m-1} + b_{ij}s^{m-2} + \cdots + \gamma_{ij},\ \ 1 \leq i,j \leq m \quad \text{...3.24}$$

The input – output disturbance relation:

$$y(s) = G(s)u(s) + \delta(s) \qquad \ldots 3.25$$

The inner-loop controller is:

$$u(s) = k(s)[\acute{r}(s) - h(s)y(s)] \qquad \ldots 3.26$$

Then, combining equations 3.25 and 3.26 yields to:

$$y(s) = \left(I_m + G(s)k(s) >< h(s)\right)^{-1}\left(G(s)k(s)\acute{r}(s) + \delta(s)\right) \qquad \ldots 3.27$$

The finite time delays in $\Gamma(s)$ ordered with $T_i \geq T_j, 1 \leq j \leq m, i \neq j$, so that the forward path gain vector arranged as

$$k(s) = \left[k_1(s)e^{-s\left(T_i - T_j\right)}, k_2(s)e^{-s\left(T_i - T_j\right)}, \ldots, k_1(s), \ldots, k_m(s)e^{-s\left(T_i - T_j\right)}\right]^T \qquad \ldots 3.28$$

And

$$h(s) = \left(h_1(s), h_2(s), \ldots, h_m(s)\right) \qquad \ldots 3.29$$

Since $\phi_j(s)\ and\ x_j(s)$ are stable, minimum phase and strictly proper or proper, then:

$$k_j(s) = k_j(s)\phi_j(s)\ \ and\ \ h_j(s) = h_j x_j(s)\ \ for\ \ 1 \leq j \leq m$$

Then $y(s)$ becomes:

$$y(s) = \left(I_m + e^{-sTi}n(s)L(s)\frac{A(s)}{d(s)}k(s) >< h(s)\right)^{-1}\left(n(s)L(s)\frac{A(s)}{d(s)}ke^{-sTi}r(s) + \delta(s)\right) 3.30$$

Where: $k = (k_1, k_2, \ldots, k_m)^T, h = (h_1, h_2, \ldots, h_m), d(s) = s^k, a_1 s^{k-1} + \cdots + a_0$

$$and\ \ deg\left(n(s)a_{ij}(s)\right) < k, \qquad for\ \ 1 \leq i, \qquad 1 \leq m$$

The determinant in equation 3.30 is:

$$det\left(I_m + e^{-sTi}n(s)L(s)\frac{A(s)}{d(s)}k(s) >< h(s)\right) = 1 + e^{-sTi}n(s) < h\frac{A(s)}{d(s)}k > \qquad \ldots 3.31$$

Where

$$< h\frac{A(s)}{d(s)}k >= [1, s, \dots, s^{m-1}]\begin{bmatrix}\gamma_{11} & \gamma_{12} & \cdots & \gamma_{mm}\\ \vdots & \vdots & \ddots & \vdots\\ b_{11} & b_{12} & \dots & b_{mm}\\ a_{11} & a_{12} & \dots & a_{mm}\end{bmatrix}\begin{bmatrix}k_1h_1\\ k_2h_2\\ \vdots\\ k_mh_m\end{bmatrix} \quad \dots 3.32$$

With gain ratio of:

$$k_2 = n_1k_1, k_3 = n_2k_1, \dots\ k_m = n_{m-1}k_1 \quad \dots 3.33$$

and

$$< hA(s)k \geq b(s) \quad \dots 3.34$$

Then equation 3.34 implies that:

$$k_1[Q]h = (b_{m-1}, b_{m-2}, \dots, b_0)^T \quad \dots 3.35$$

Where

$$Q =$$

$$\begin{bmatrix}\gamma_{11} + \gamma_{12}n_1 + \gamma_{1m}n_{m-1} & \vdots & \gamma_{21} + \gamma_{22}n_1 + \gamma_{2m}n_{m-1} & \vdots & \cdots & \gamma_{m1} + \gamma_{m2}n_1 + \gamma_{mm}n_{m-1}\\ \vdots & \vdots & \vdots & \vdots & \cdots & \vdots\\ b_{11} + b_{12}n_1 + b_{1m}n_{m-1} & \vdots & b_{21} + b_{22}n_1 + b_{2m}n_{m-1} & \vdots & \cdots & b_{m1} + b_{m2}n_1 + b_{mm}n_{m-1}\\ a_{11} + a_{12}n_1 + a_{1m}n_{m-1} & \vdots & a_{21} + a_{22}n_1 + a_{2m}n_{m-1} & \vdots & \cdots & a_{m1} + a_{m2}n_1 + a_{mm}n_{m-1}\end{bmatrix}$$

By selecting n values of the above equation, the performance index becomes:

$$J = (1 + {n_1}^2 + {n_2}^2 + \cdots + {n_{m-1}}^2)b^T(Q^{-1})^TQ^{-1}b$$

Chapter 4 – Results and Discussion

4.1 Least Effort Controller Theory:

4.1.1 Least Effort Controller Technique:

The system transfer function can be factorized as follows:

$$\mathbf{G}(\mathbf{s}) = \mathbf{L}(\mathbf{s})\frac{\mathbf{A}(\mathbf{s})}{\mathrm{d}(\mathrm{s})}\,\mathbf{R}(\mathbf{s})\boldsymbol{\Gamma}(\mathbf{s})$$

leads to:

$$\mathbf{L}(\mathbf{s}) = \boldsymbol{\Gamma}(\mathbf{s}) = \mathbf{R}(\mathbf{s}) = \mathbf{I}$$

$$\mathbf{A}(\mathbf{s}) = \begin{bmatrix} 1.2191 & -11.11(s+0.195) \\ -6.25(s+0.1758) & 1.0339 \end{bmatrix}$$

$$\mathrm{d}(\mathrm{s}) = s^2 + 0.3708s + 0.0343$$

Proceeding with the design, we compute:

$$\langle \mathbf{hA}(\mathbf{s})\mathbf{k}\rangle = [h_1 \quad h_2]\begin{bmatrix} 1.2191 & -11.11(s+0.195) \\ -6.25(s+0.1758) & 1.0339 \end{bmatrix}\begin{bmatrix} k_1 \\ k_2 \end{bmatrix}$$

$$= [1 \quad s]\begin{bmatrix} 1.2191 & -2.16645 & -1.09875 & 1.0339 \\ 0 & -11.11 & -6.25 & 0 \end{bmatrix}\begin{bmatrix} k_1h_1 \\ k_2h_1 \\ k_1h_2 \\ k_2h_2 \end{bmatrix}$$

To obtain the matrix $\mathbf{Q}$, k_1 and k_2 are first related using $\mathrm{k}_2 = \mathrm{n}\mathrm{k}_1$and the result substituted into the preceding equation. This leads to:

$$\mathbf{Q} = \begin{bmatrix} 1.2191 - 2.16645n & -1.09875 + 1.0339n \\ -11.11n & -6.25 \end{bmatrix}$$

4.1.2 Inner loop

The system takes the form:

$$\langle \mathrm{hA(s)k} \rangle = \frac{\mathrm{b(s)}}{\mathrm{d(s)}}$$

where $b(s) = b_0(s + x)$. To obtain b_0 and x, the root locus diagram of $\frac{\mathrm{b(s)}}{\mathrm{d(s)}} = -1$ is drawn, first with $b(s) = 1$. The result is shown in Figure 4.1.

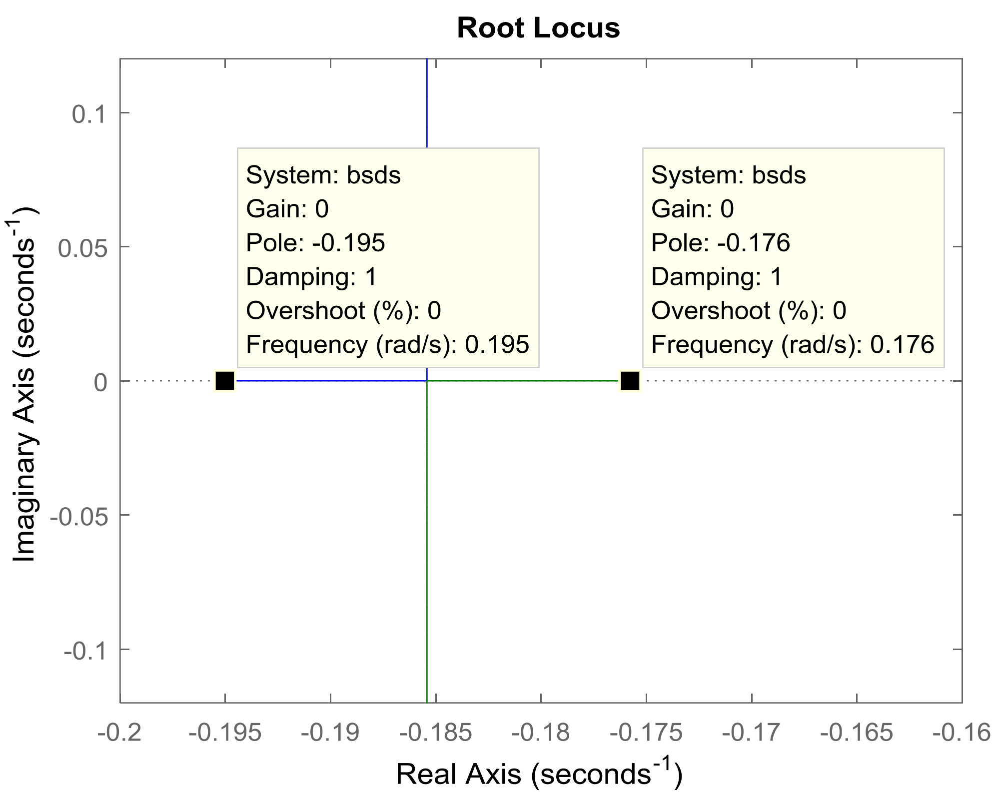

Figure 4.1 Root locus of $\frac{1}{\mathrm{d(s)}}$

In this system, the dominant pole is located at $s = 0.176$. To cancel the effect of the dominant pole, a zero is introduced at $s = -0.18$. Setting $b_0 = 1$ leads to:

$$\frac{\mathrm{b(s)}}{\mathrm{d(s)}} = \frac{(s + 0.18)}{s^2 + 0.3708s + 0.0343}$$

The next task in the process is the determination of n and this is done using the performance index J defined as follows:

$$\mathrm{J(n)} = (1 + n^2)\mathbf{b}^{\mathrm{T}}(\mathbf{Q}^{-1})^{\mathrm{T}}\mathbf{Q}^{-1}\mathbf{b}$$

where

$$\mathbf{b} = \begin{bmatrix} 1 \\ 0.18 \end{bmatrix}$$

The value of J evaluates to:

$$\mathrm{J(n)} = \frac{(114953870115925n^4 + 6957430190064n^3 + 151631450602394n^2)}{(11486629\mathrm{n}^2 + 1333200\mathrm{n} - 7619375)^2} \ldots$$

$$+ \frac{6957430190064n + 36677580486469}{(11486629\mathrm{n}^2 + 1333200\mathrm{n} - 7619375)^2}$$

To obtain the value of n that leads to a global minimum of J, a plot of J against n is first produced to find the initial points for numerical minimization using MATLAB. Figure 4.2 shows the performance index plot. From Figure 4.2, the absolute minimum of the function is around $\mathrm{n} = 0$. The starting point for minimization can be chosen to be 0.1. The value of n that minimizes the function is -1.987×10^{-5}. Substituting this value in the expression for **Q** results in:

$$\mathbf{Q} = \begin{bmatrix} 1.3008 & -1.1377 \\ 0.4189 & -6.25 \end{bmatrix}$$

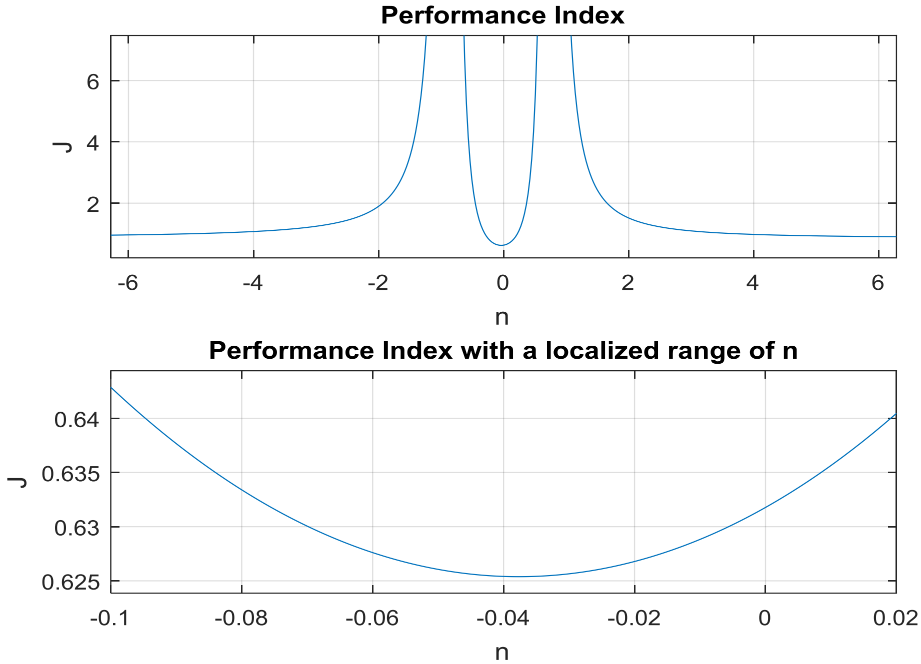

Figure 4.2 Performance index plot

From **Q**, **b** and $k_1 = 1$, the value of $h(s)$ is computed.

$$h(s) = \frac{\mathbf{Q}^{-1}}{k_1}\mathbf{b} = \begin{bmatrix} 0.7899 \\ 0.0241 \end{bmatrix}$$

To obtain k_2, the expression $k_2 = nk_1$ is used, leading to:

$$\mathbf{k} = \begin{bmatrix} 1 \\ -0.0377 \end{bmatrix}$$

Since $R(s) = 1$, $\mathbf{k}(\mathbf{s})$ is expressed as:

$$\mathbf{k}(s) = \mathbf{k}R(s) = \mathbf{k}$$

and

$$\mathbf{k}(0) = \mathbf{k}$$

4.1.3 Outer Loop

The dc gain of the open loop system is obtained as:

$$\mathbf{G}(0) = \begin{bmatrix} 35.5518 & -32.0513 \\ -63.2031 & 30.1580 \end{bmatrix}$$

To limit the steady state interaction due to output coupling to a maximum of 1%, the following definition is made:

$$\mathbf{S}_s = \begin{bmatrix} 1 & 0.01 \\ 0.01 & 1 \end{bmatrix}$$

For the outer loop feedback gain, a value should be selected in the range $0 < f < 1$. This implies that the value of f can be varied within the range in order to select the best control strategy. After selecting a value $f = f_s$ the computation of the feed forward gain matrix **P** and feedback gain matrix **H** can be done as shown below.

$$\mathbf{F} = \begin{bmatrix} f_s & 0 \\ 0 & f_s \end{bmatrix}$$

$$\mathbf{P} = \left(\mathbf{G}(0)^{-1} + \mathbf{k}(0) >< \mathbf{h}(0)\right)\mathbf{S}_s(\mathbf{I} - \mathbf{F}\mathbf{S}_s)^{-1}$$

$$\mathbf{H} = \mathbf{P}^{-1}\mathbf{k}(\mathrm{s}) >< \mathbf{h}(\mathrm{s}) + \mathbf{F}$$

The least effort controller Simulink model is as shown in Appendix.

The dc gain of the open loop system is obtained as:

$$\mathbf{G}(0) = \begin{bmatrix} 208251.35 & -5219.21 \\ -173.47 & 4881.65 \end{bmatrix}$$

4.1.4 Scaling f_s in Different Conditions

$f_s = 0.1$

When $f_s = 0.1$, feed forward and feedback gain matrices are obtained as:

$$\mathbf{P} = \begin{bmatrix} 0.8424 & -0.0012 \\ -0.1072 & -0.0436 \end{bmatrix}$$

$$\mathbf{H} = \begin{bmatrix} 1.0354 & 0.0286 \\ -1.6162 & 0.0506 \end{bmatrix}$$

The resulting graphs are shown in Figure 4.3 to Figure 4.6 with each showing the outputs when one of the possible four inputs is active and the others are inactive.

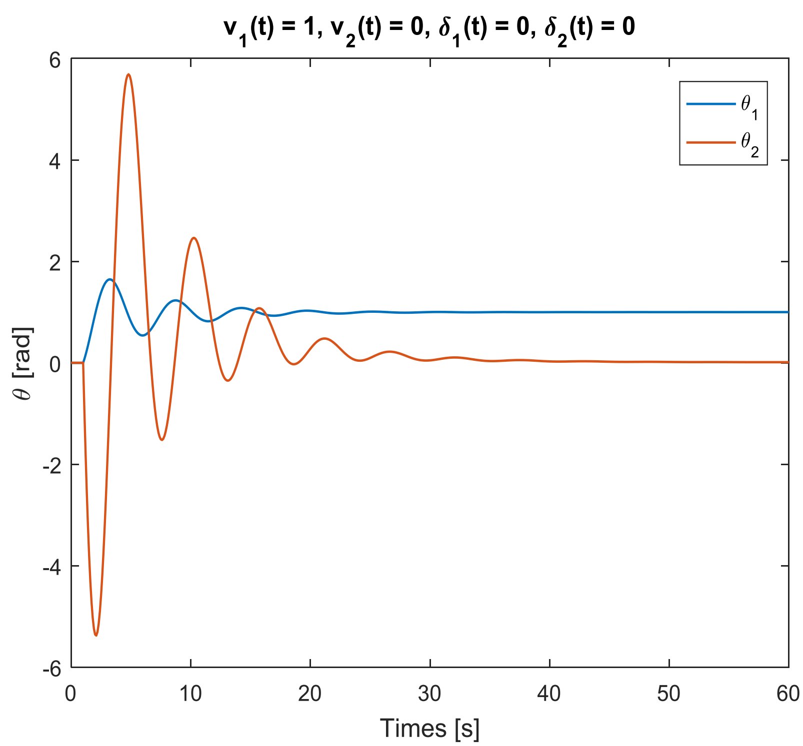

Figure 4.3 Step response of the system with only V1 active

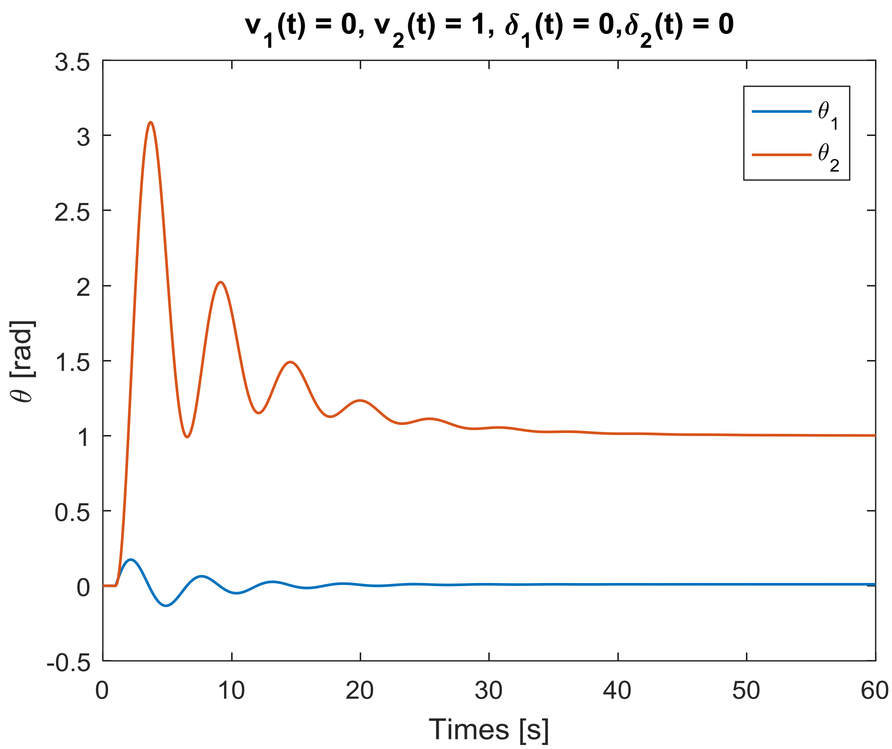

Figure 4.4 Step response of the system with only V2 active

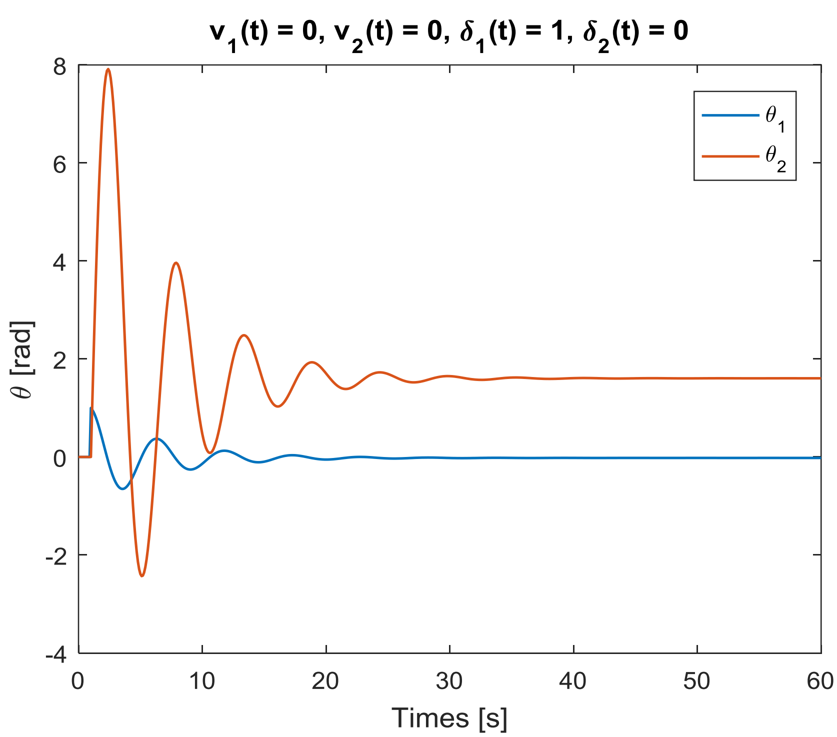

Figure 4.5 Response of the system to the first disturbance input

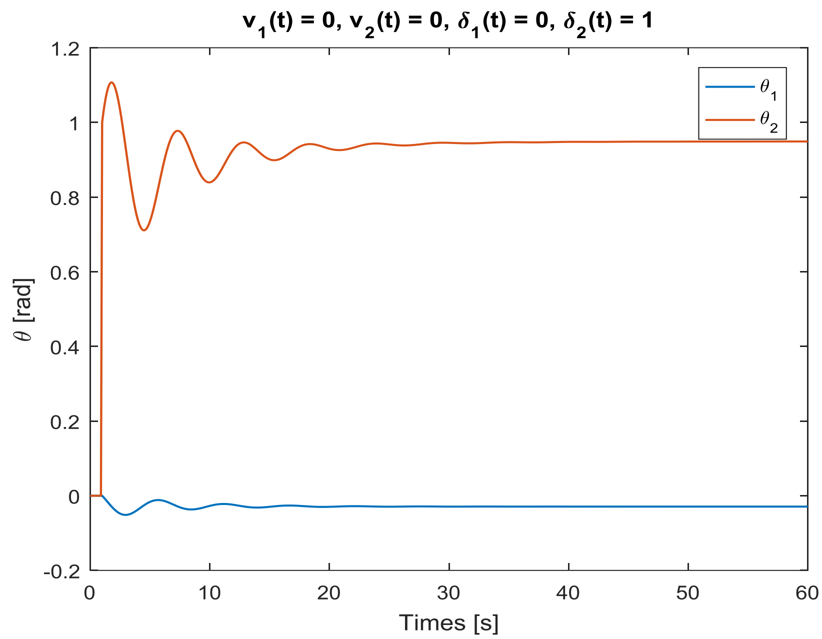

Figure 4.6 Response of the system to the second disturbance input

The results show that at $f_s = 0.1$ the system is not able to reject all the disturbances and takes about 30s to reach steady state.

$f_s = 0.3$

When $f_s = 0.3$, feed forward and feedback gain matrices are obtained as:

$$\mathbf{P} = \begin{bmatrix} 1.0831 & 0.0019 \\ -0.1380 & -0.0565 \end{bmatrix}$$

$$\mathbf{H} = \begin{bmatrix} 1.0315 & 0.0223 \\ -1.2593 & 0.2615 \end{bmatrix}$$

Setting each of the inputs to a step input in turns produces the results in Figure 4.7 to Figure 4.10.

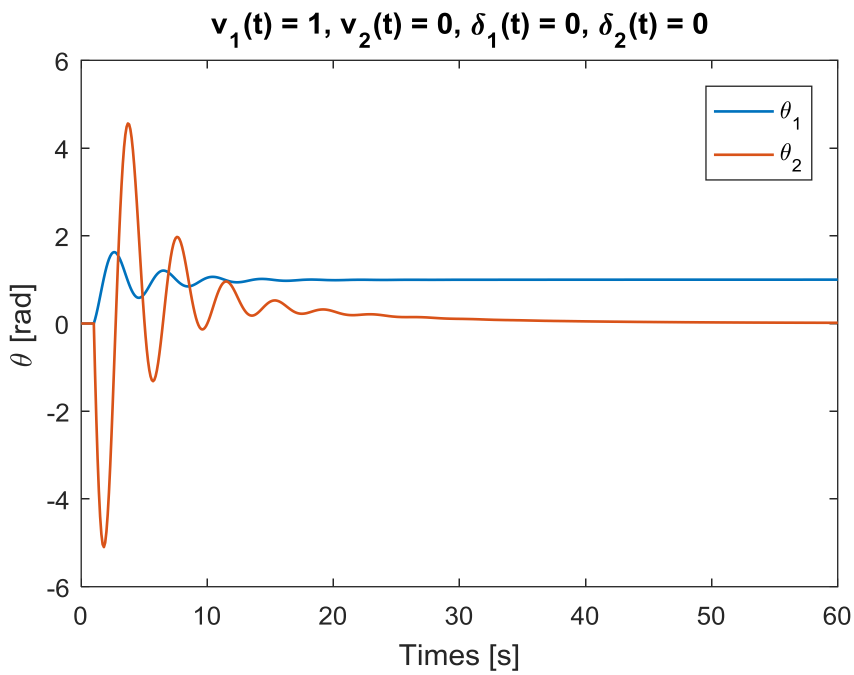

Figure 4.7 Outputs with V1 set to 1

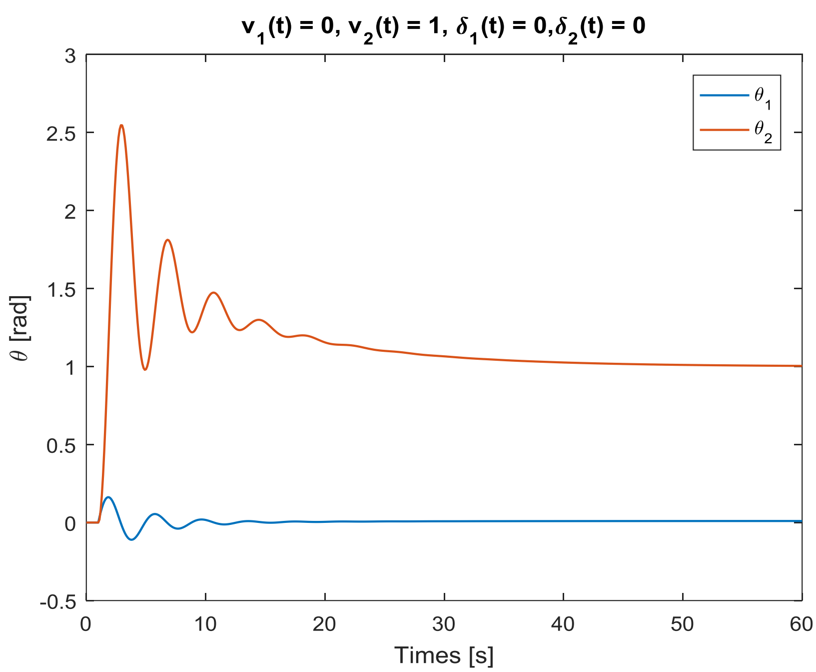

Figure 4.8 Outputs with V2 set to 1

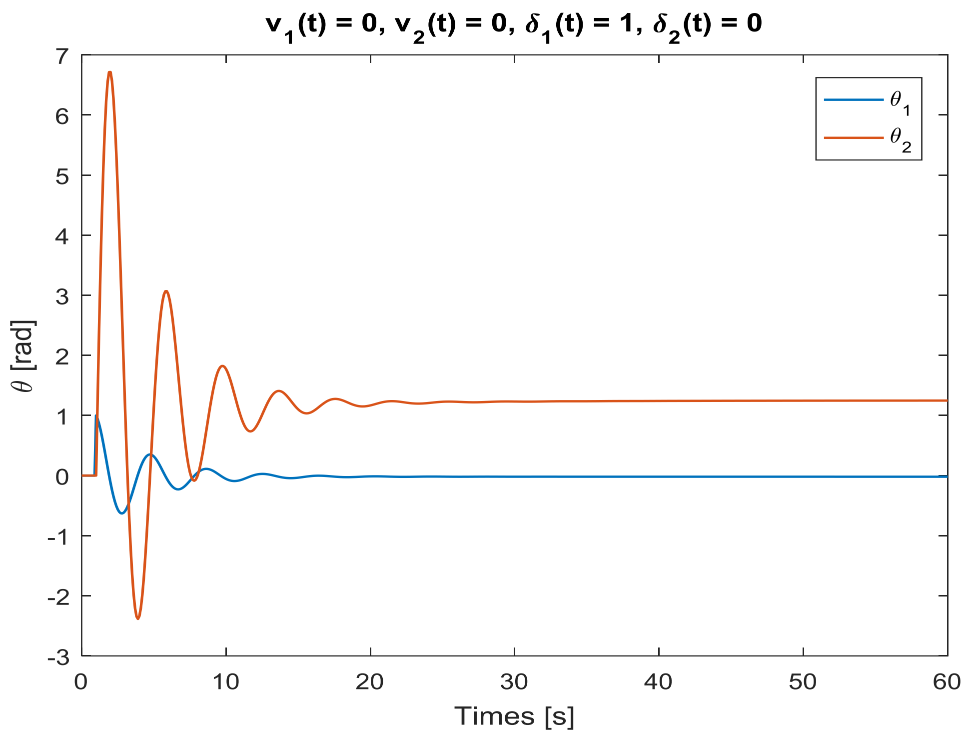

Figure 4.9 Outputs with the first disturbance set to 1

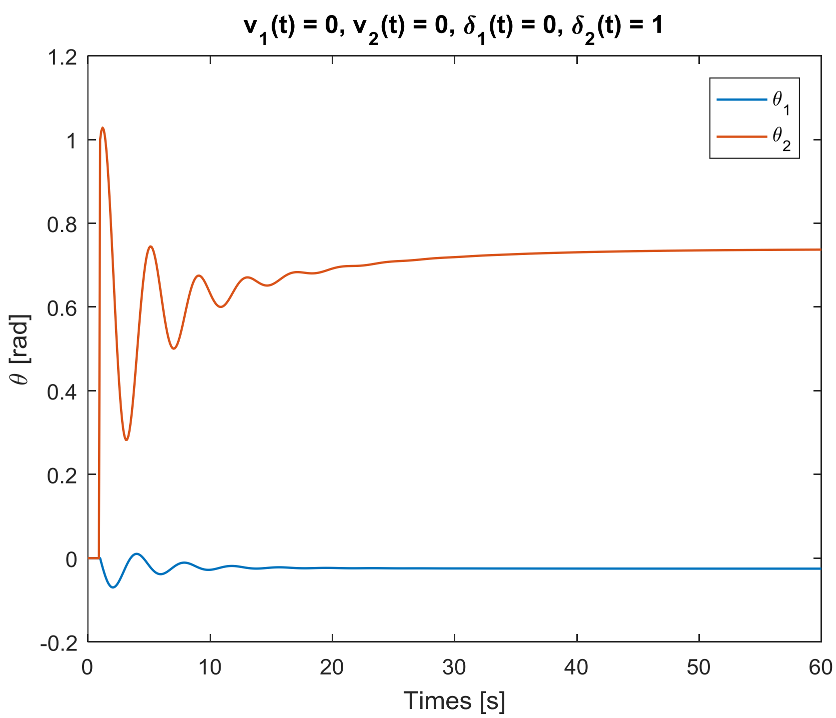

Figure 4.10 Outputs with the second disturbance set to 1

The steady state response time is now reduced to about 25s. Disturbance is not rejected at the second output, whereas; first output only rejects the disturbance. The steady state error that is caused by the disturbance is also reduced as compared to the case when $f_s = 0.1$.

$f_s = 0.65$

When $f_s = 0.65$, feed forward and feedback gain matrices are obtained as:

$$\mathbf{P} = \begin{bmatrix} 2.1668 & 0.0348 \\ -0.2777 & -0.1170 \end{bmatrix}$$

$$\mathbf{H} = \begin{bmatrix} 1.0247 & 0.01145 \\ -0.6349 & 0.6306 \end{bmatrix}$$

Setting each of the inputs to a step input in turns produces the results in Figure 4.11 to Figure 4.14.

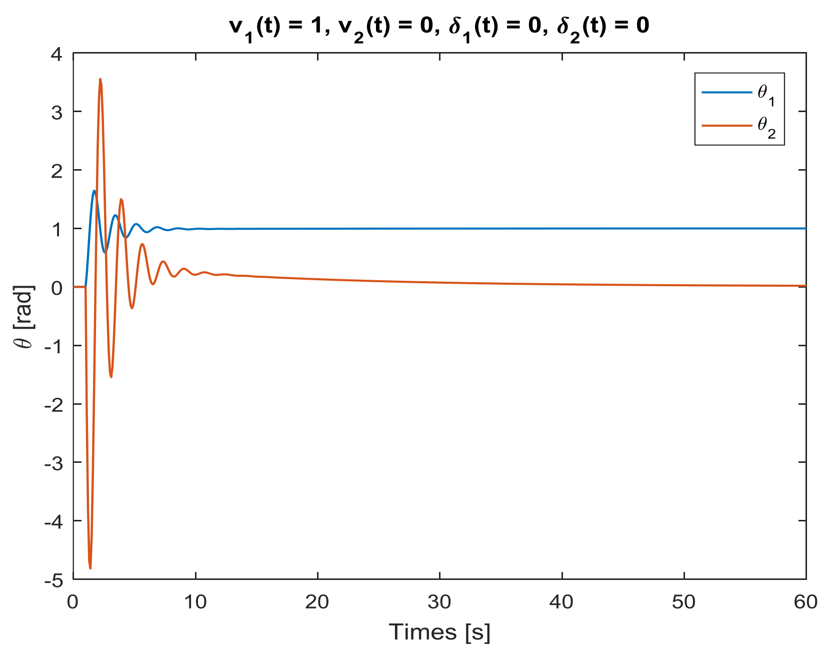

Figure 4.11 Outputs with V1 set to 1

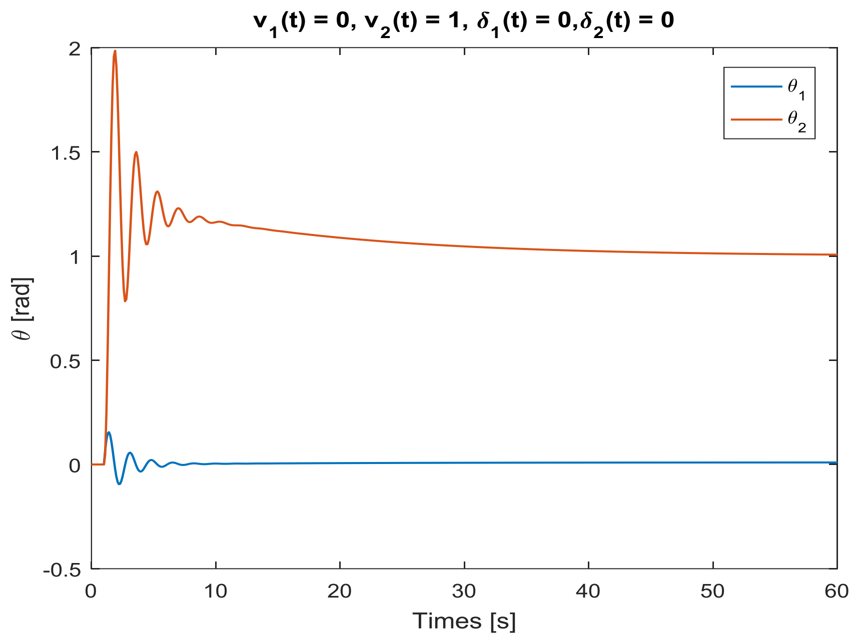

Figure 4.12 Outputs with V2 set to 1

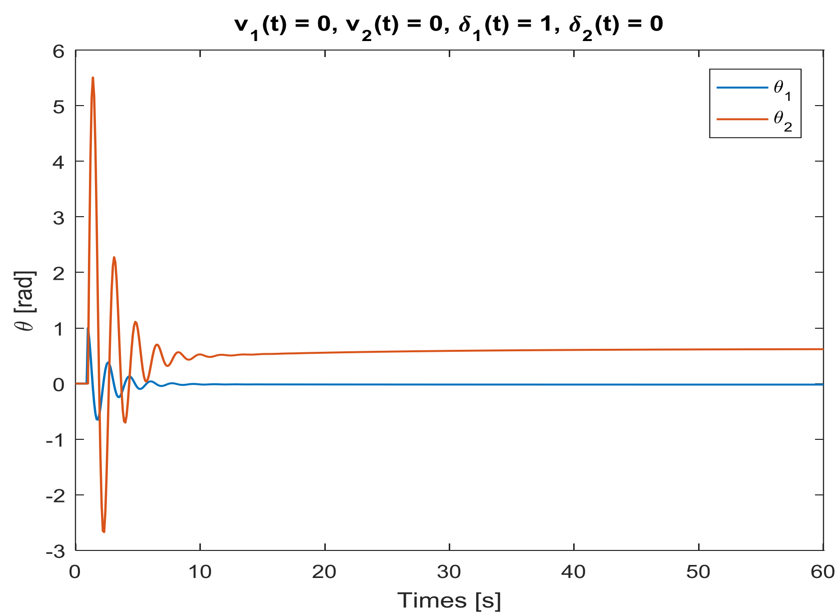

Figure 4.13 Outputs with the first disturbance set to 1

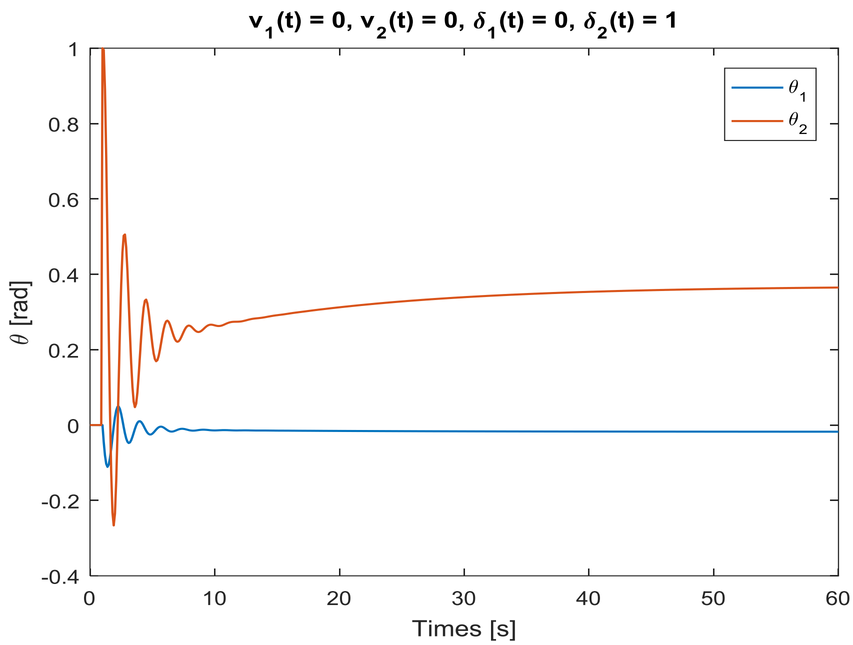

Figure 4.14 Outputs with the second disturbance set to 1

The settling time is reduced further for most inputs save for the second disturbance input. The steady state errors also reduce further as compared to the case when $f_s = 0.63$.

$f_s = 0.85$

When $f_s = 0.85$, feed forward and feedback gain matrices are obtained as:

$$\mathbf{P} = \begin{bmatrix} 5.07 & 0.2747 \\ -0.66 & -0.2984 \end{bmatrix}$$

$$\mathbf{H} = \begin{bmatrix} 1.0209 & 0.0052 \\ -0.2780 & 0.8415 \end{bmatrix}$$

Setting each of the inputs to a step input in turns produces the results in Figure 4.15 to Figure 4.18.

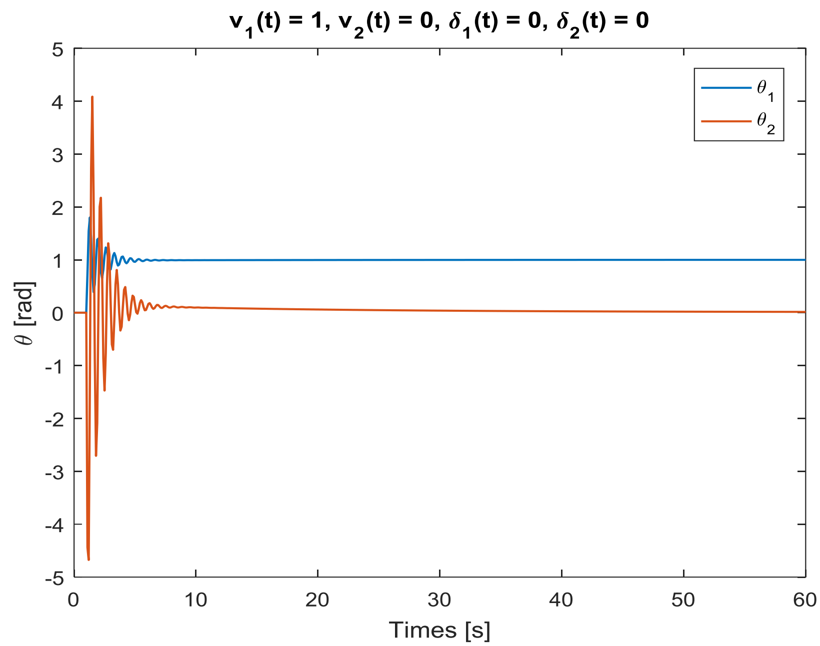

Figure 4.15 Outputs with V1 set to 1

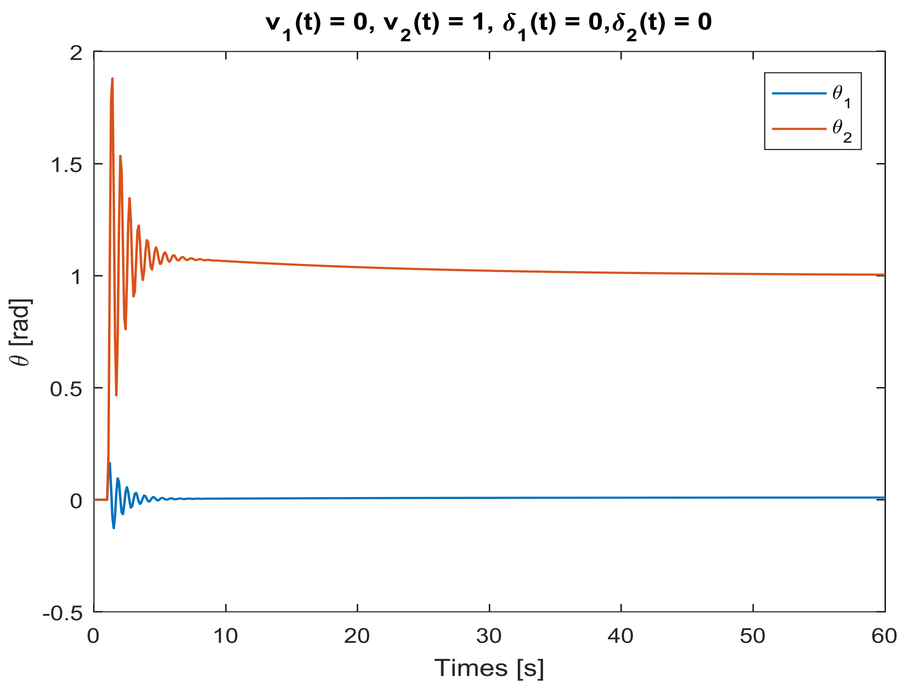

Figure 4.16 Outputs with V2 set to 1

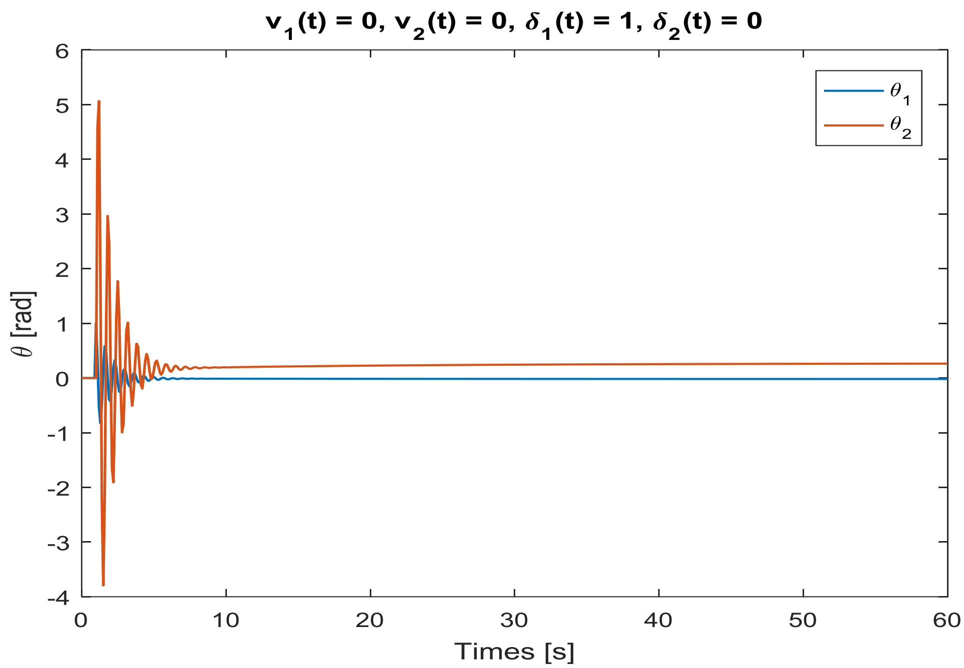

Figure 4.17 Outputs with the first disturbance set to 1

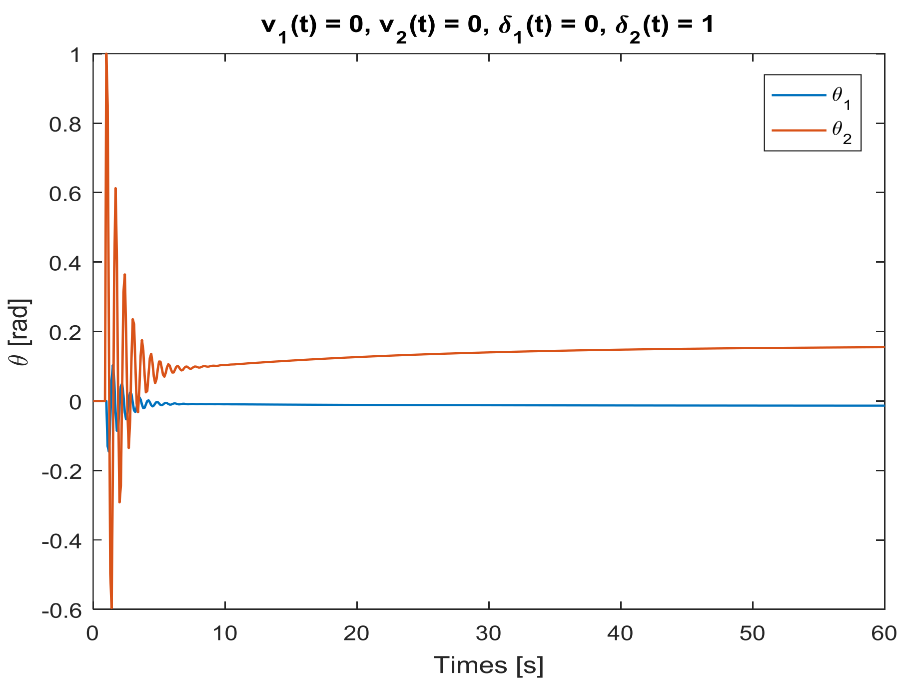

Figure 4.18 Outputs with the second disturbance set to 1

The input leading to the most concern is the first disturbance input. Even through a further reduction of steady state errors is observed compared to the case when $f_s = 0.65$, the peak response to the first disturbance output is almost at 5.

Overall, to view the performance of the system when all the inputs are active, all the inputs should be set to 1. The choice of the correct value of f_s depends upon the design specifications that are to be met for a system to function with the desired response characteristics. For instance, selecting $f_s = 0.75$ and setting all the inputs to the system to 1 gives the result shown in Figure 4.19. The results show a steady state error of about 0.7 on θ_2. By contrast, the open loop response of the system with all inputs active is shown in Figure 4.20.

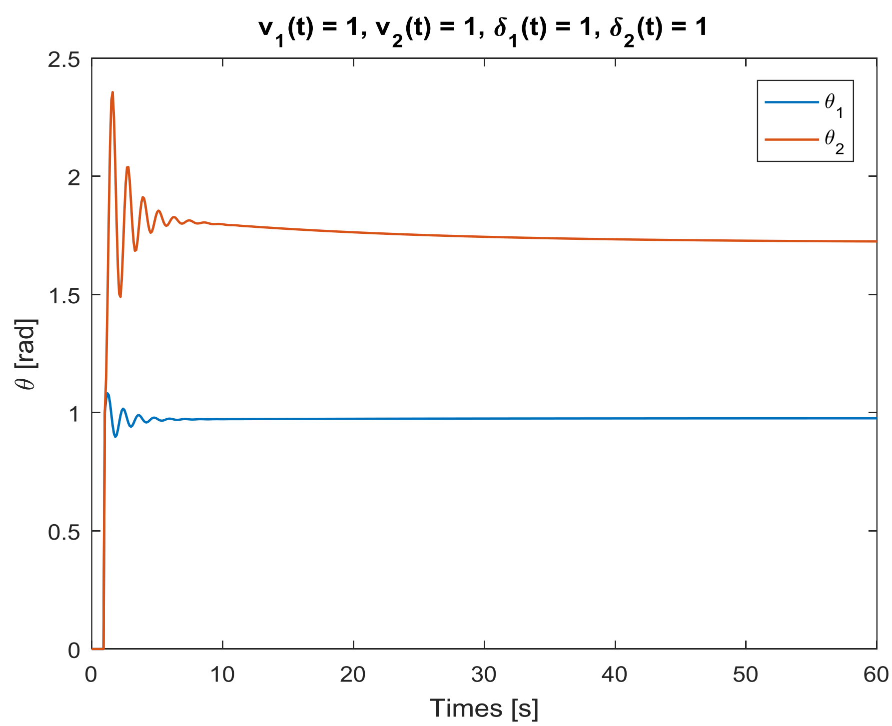

Figure 4.19 Outputs with all inputs set to 1 and $f_s = 0.75$

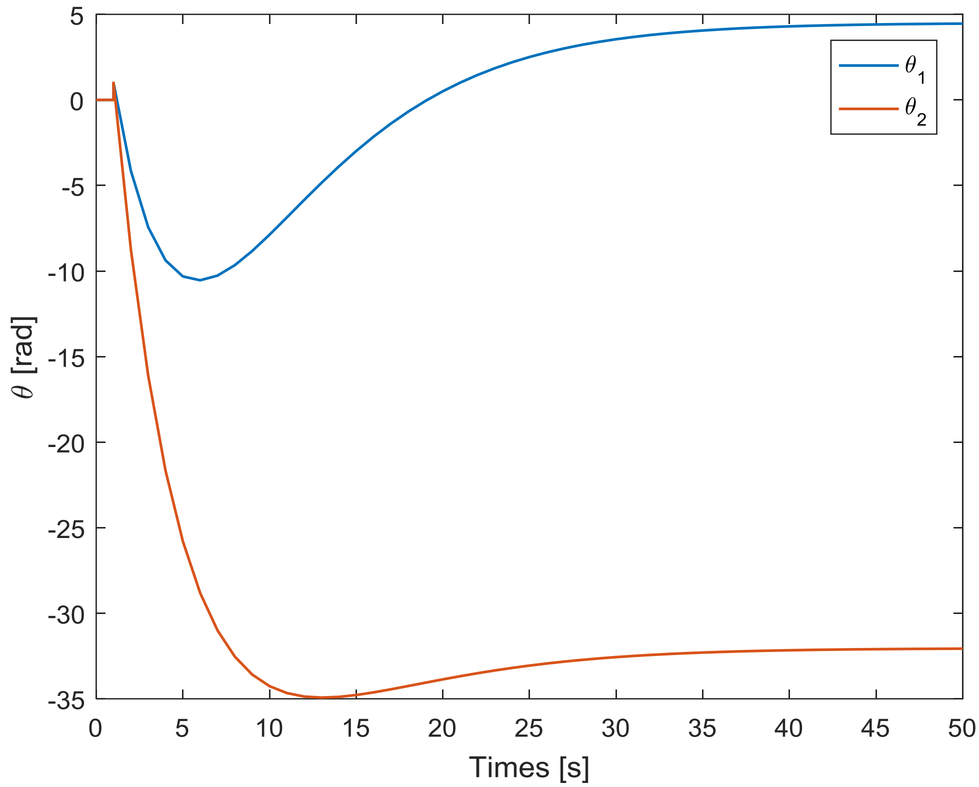

Figure 4.20 System response of the open loop system with all the disturbances and the inputs active

Chapter 5 – Conclusions and Recommendations

5.1 Conclusion:

This dissertation is to fulfil the understanding of modelling and simulating the multivariable system. The system proposed in the research is the marine propulsion system, which is used for various applications and was chosen to test and evaluate the stability of the system using one of the techniques, which is the least effort controller method. For achieving the target, mathematical methodoligy, modeling and simulations approaches were solved to verify that the model is being designed and behaving as desired where the factors involved in the system are functioning properly.

In the dissertation modeling of the propulsion system, the target is to improve the stability of the system in different disturbances condition, control it by changing the system parameters and compare the outputs with the set points then try to recover the disturbances effects by scaling the gain values. In the end, the stability is achieved that will reduce the fuel consumption and reduce the pollution. However, for proving system that is more reliable in order to implement it in further then quality assurance is important. The data obtained at low speeds of the turbocharger is lacking in some areas and hence further testing is required to insure system more reliable and stable. The simulations in MATLAB shows that the developed model is performing well when the engine is operating under low loads and on low speeds of turbochargers. Since the linear interpolation is a normal approach and hence it cannot extrapolate, thus the results obtained by simulation are suggesting to use parameter fitted models instead of the linear interpolation of turbocharger maps. Moreover, the modeling of the marine propulsion system smooth the way for exhaust circulation of gas and development of transient air-to-fuel ratio.

The methodology of Least Effort Control (LEC) is found out to be reliable and generating the desired results and fulfil the requirements of a propulsion system. The response of the controller found out to be stable, well behaved and quick as well. Despite the strong coupling, the controller was able to succeed in reducing the interaction of the output as specified. This is also reflecting the power of the design philosophy that is also playing role in giving the freedom for enhancing the closed loop response and the performance of the multivariable system, also enhancing the recovery rates of the disturbance. The strategy adopted is minimising the control. According to the chosen strategy, it is seen that LEC is satisfying all the objectives of the research hence it proves that this method is appropriate for gaining the stability in the system. The reasons why this method is suitable and giving out interesting results is first of all this method is the simplest one, hence it becomes ideal for the purpose of implementation having very low cost of application. Secondly, the performance of this method can be easily compared with the other methods even when the disturbance is also present. Third, as the name implies this method has proven that it involves least effort, which has resulted in gaining certain advantages such as improvements in the fuel consumption of the engine and low cost of operations.

One of the very few problems that are faced in the least effort control method is that it is not considered as a reliable source of implementation when solving linear time invariant system (LTI) because of the complexity in the system transfer function matrix. For solving this problem to a certain extent approximations are needed which would reduce the order of the transfer functions then it would fit in the formulas. Furthermore, the systems that are consisting of two inputs and two outputs are complicating the optimization process required for control effort.

5.2 Recommendations:

There are different recommendations that are based on the understanding of this research and were also noticed while doing the literature review that these points have not been taken into consideration by the scholars as well. The first recommendation is that a realistic model is needed for the heat loss in the exhaust manifold. The engine should also be extended by including the VAT, EGR and/or wastegate with the design algorithm also included for controlling the air-to-fuel ratio and to reduce pollutants. The analysis must also be done on the fluctuations in the torque of propeller and on the basis of that a robust control algorithm should be developed for preventing the overspeed of the engine by reducing the torque losses. The model of propeller should be extended to all the four quadrants. A model of propeller should be included for the controllable pitch propellers. Linearization of the propulsion model should also be performed by incorporation of parameter tuning and gain scheduling. A model for controlling the speed of the engine can also be developed based on nonlinear approach and the verification of exponential flow of compressor model should be done by comparing it with other maps of compressor. Furthermore, the comparison of performance by using the method of rectangular hyperbolas is also suggested.

It is recommended that the other methods should be applied in the future as well because they contain certain factors that make them stand-out especial. It is also recommended that these methods should be applied to more complex models such as the systems having more than two inputs and two outputs for checking their results. Both the techniques of optimization and approximation must be kept into consideration while doing any sort of modeling in the future. One of the recommendations regarding the design package of the controls that were analyzed in the Least Effort Control method, over the entire operating region of marine propulsion system should be investigated and tested by comparing it with the other methodologies.

References

Altosole, M., Benvenuto, G., Figari, M. and Campora, U., 2012. Dimensionless numerical approaches for the performance prediction of marine waterjet propulsion units. *International Journal of Rotating Machinery*, *2012*.

Armstrong, M.J., Ross, C.A., Blackwelder, M.J. and Rajashekara, K., 2012. Propulsion system component considerations for NASA N3-X turboelectric distributed propulsion system. *SAE International Journal of Aerospace*, *5*(2012-01-2165), pp.344-353.

Balashov, S., 2011. Design of marine generators for alternative diesel-electric power systems.

Bø, T.I., Johansen, T.A., Sørensen, A.J. and Mathiesen, E., 2016. Dynamic consequence analysis of marine electric power plant in dynamic positioning. *Applied Ocean Research*, *57*, pp.30-39.

De Santiago, J., Bernhoff, H., Ekergård, B., Eriksson, S., Ferhatovic, S., Waters, R. and Leijon, M., 2012. Electrical motor drivelines in commercial all-electric vehicles: A review. *IEEE Transactions on Vehicular Technology*, *61*(2), pp.475-484.

Dimopoulos, G.G., Georgopoulou, C.A., Stefanatos, I.C., Zymaris, A.S. and Kakalis, N.M., 2014. A general-purpose process modelling framework for marine energy systems. *Energy conversion and management*, *86*, pp.325-339.

Doerry, N., Amy, J. and Krolick, C., 2015. History and the status of electric ship propulsion, integrated power systems, and future trends in the US Navy. *Proceedings of the IEEE*, *103*(12), pp.2243-2251.

El-Gohary, M.M., 2012. The future of natural gas as a fuel in marine gas turbine for LNG carriers. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *226*(4), pp.371-377.

Fletcher, S.D.A., Elders, I.M., Norman, P.J., Galloway, S.J., Booth, C.D., Burt, G.M., McCarthy, J. and Hill, J.E., 2010. The impact of incorporating skin effect on the fault analysis and protection system performance of DC marine and aerospace power systems.

Geertsma, R.D., Negenborn, R.R., Visser, K. and Hopman, J.J., 2017. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. *Applied Energy*, *194*, pp.30-54.

Gully, B.H., 2012. *Hybrid powertrain performance analysis for naval and commercial ocean-going vessels* (Doctoral dissertation).

Hansen, J.F. and Wendt, F., 2015. History and state of the art in commercial electric ship propulsion, integrated power systems, and future trends. *Proceedings of the IEEE*, *103*(12), pp.2229-2242.

Hansen, J.F., Ådnanes, A.K. and Fossen, T.I., 2001. Mathematical modelling of diesel-electric propulsion systems for marine vessels. *Mathematical and Computer Modelling of Dynamical Systems*, *7*(3), pp.323-355.

Ji, B., Luo, X.W., Wu, Y.L., Liu, S.H., Xu, H.Y. and Oshima, A., 2010. Numerical investigation of unsteady cavitating turbulent flow around a full scale marine propeller. *Journal of Hydrodynamics, Ser. B, 22*(5), pp.747-752.

Kanellos, F.D., Prousalidis, J.M. and Tsekouras, G.J., 2014. Control system for fuel consumption minimization–gas emission limitation of full electric propulsion ship power systems. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *228*(1), pp.17-28.

Karlsen, A.T., 2012. *On Modeling of a Ship Propulsion System for Control Purposes* (Master's thesis, Institutt for teknisk kybernetikk).

Kawamura, T., Ouchi, K. and Nojiri, T., 2012. Model and full scale CFD analysis of propeller boss cap fins (PBCF). *Journal of marine science and technology*, *17*(4), pp.469-480.

Kobougias, I., Tatakis, E. and Prousalidis, J., 2013. PV systems installed in marine vessels: technologies and specifications. *Advances in Power Electronics*, *2013*.

Lamden, J., 2012. Hybrid Propulsion. *The Reference Point*, pp.6-11.

Li, Z.X., Yan, X.P., Qin, L., Yuan, C.Q. and Peng, Z.X., 2013. Model reference robust control for marine propulsion systems with model uncertainty caused by hull deformation. *Journal of Marine Science and Technology*, *21*(4), pp.400-409.

Liu, S., Papanikolaou, A. and Zaraphonitis, G., 2011. Prediction of added resistance of ships in waves. *Ocean Engineering*, *38*(4), pp.641-650.

Papanikolaou, A., 2010. Holistic ship design optimization. *Computer-Aided Design*, *42*(11), pp.1028-1044.

Petersen, L.J., Hoffman, D.J., Borraccini, J.P. and Swindler, S.B., 2010. Next-Generation Power and Energy: Maybe Not So Next Generation. *Naval Engineers Journal*, *122*(4), pp.59-74.

Rajashekara, K. (2013). Present status and future trends in electric vehicle propulsion technologies. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *1*(1), 3-10.

Rzadki, W. and Horn, H.S., Siemens Aktiengesellschaft, 2013. *Method and apparatus for operation of a marine vessel hybrid propulsion system*. U.S. Patent 8,545,278.

Seo, J.H., Seol, D.M., Lee, J.H. and Rhee, S.H., 2010. Flexible CFD meshing strategy for prediction of ship resistance and propulsion performance. *International Journal of Naval Architecture and Ocean Engineering*, *2*(3), pp.139-145.

Skjong, E., Rødskar, E., Molinas Cabrera, M.M., Johansen, T.A. and Cunningham, J., 2015. The marine vessel's electrical power system: From its birth to present day.

Spichartz, M., Staudt, V. and Steimel, A., 2013, April. Modular multilevel converter for propulsion system of electric ships. In *Electric Ship Technologies Symposium (ESTS), 2013 IEEE* (pp. 237-242). IEEE.

Song, J., Song, Y. and Gu, C.W., 2015. Thermodynamic analysis and performance optimization of an Organic Rankine Cycle (ORC) waste heat recovery system for marine diesel engines. *Energy*, *82*, pp.976-985.

Theotokatos, G. and Livanos, G., 2013. Techno-economical analysis of single pressure exhaust gas waste heat recovery systems in marine propulsion plants. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *227*(2), pp.83-97.

Theotokatos, G. and Tzelepis, V., 2015. A computational study on the performance and emission parameters mapping of a ship propulsion system. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *229*(1), pp.58-76.

Whalley, R. and Ebrahimi, M. (2006). Multivariable System Regulation. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* May 1, 2006 vol. 220 no.5, pp. 653-667.

Wu, N.E., Thavamani, S., Zhang, Y. and Blanke, M., 2006. Sensor fault masking of a ship propulsion system. *Control Engineering Practice*, *14*(11), pp.1337-1345.

Yaxin, C. and Yaxu, L., 2012. Study on Development of Marine Integrated Power System [J]. *Marine Electric & Electronic Engineering*, *1*, p.018.

Yutao, C., Fanming, Z. and Jiaming, W., 2012. Integrated Design Platform for Marine Electric Propulsion System. *Energy Procedia*, *17*, pp.540-546.

Zhang, G., Zhao, Y., Li, T. and Zhu, X., 2014. Propeller excitation of longitudinal vibration characteristics of marine propulsion shafting system. *Shock and Vibration*, *2014*.

APPENDIX

```
close all
clear
clc

% Mechanical Parameters
C1 = 0.99;
C2 = 1.06;
C3 = 0.17;
J1 = 0.87;
J2 = 0.36;
JL = 1.56;
K1 = 0.16;
K2 = 0.09;


% Electrical Parameters
L1  = 1;
R1  = 0.1758;
Kf1 = 1;
L2  = 1;
R2  = 0.195;
Kf2 = 1;

% transformation matrix
den1 = [L1 R1];
den2 = [L2 R2];
den22 = conv([J2*JL J2*C3+JL*C2 J2*K2+C2*C3+(K1+K2)*JL ...
    C2*K2+C3*(K1+K2) K1*K2],den2);

g11 = tf(Kf1,conv([J1 C1 K1],den1));
g21 = tf(Kf1,-K2*den1);
g12 = tf(Kf2,-K1*den2);
g22 = tf(Kf2*[JL C3 K2],den22);

G = [ g11, g12;
      g21, g22];
% figure, nyquist(H);
zpk(G)
zpk(minreal(G,0.1))
G = minreal(G,0.1);
% figure, nyquist(G);

% modify further
% constants
[~, p1, k1] = zpkdata(G(1,1));
[~, p2, k2] = zpkdata(G(2,2));
k11 = abs(k1/p1{1}(1));
k22 = abs(k2/p2{1}(1));
% transfer functions
g11m = tf(k11, conv([1 -p1{1}(2)],[1 -p1{1}(3)]));
g22m = tf(k22, conv([1 -p2{1}(2)],[1 -p2{1}(3)]));
g22 = G(2,2);
```

```
Gm = [ g11m g12;
       g21  g22m];
% step responses
figure, step(g11, g11m), legend('Original', 'Reduced')
ylabel('Pitch \theta_1 due to V_1')
figure, step(g22, g22m), legend('Original', 'Reduced')
ylabel('Pitch \theta_2 due to V_2')

% nyquist plots
figure, nyquist(G,Gm), legend('Original', 'Reduced')

% dcoeff
[~, dcoeff] = tfdata(Gm(1,1));
bsds = tf(1, dcoeff{1});
figure, rlocus(bsds)
set(gca, 'XLim', [-0.2 -0.16])

% tfdata
[num, den] = tfdata(Gm);

% simulate open loop
model = 'open_loop.mdl';
% cases
% Case 1: v1 = 1, v2 = 0, d1 = 0, d2 = 0
V = [1 0];
d = [0 0];
sim(model)
ScopeData
t = ScopeData.time;
x1 = ScopeData.signals(1).values;
x2 = ScopeData.signals(2).values;
figure, plot(t, [x1, x2], 'LineWidth', 1)
xlabel('Times [s]'), ylabel('\theta [rad]'), legend('\theta_1', ...
    '\theta_2');
set(gca,'xlim',[0 50])
% Case 2: v1 = 0, v2 = 1, d1 = 0, d2 = 0
V = [0 1];
sim(model)
t = ScopeData.time;
x1 = ScopeData.signals(1).values;
x2 = ScopeData.signals(2).values;
figure, plot(t, [x1, x2], 'LineWidth', 1)
xlabel('Times [s]'), ylabel('\theta [rad]'), legend('\theta_1', ...
    '\theta_2');
set(gca,'xlim',[0 50])

% least effort controller
G0 = dcgain(Gm);

% Obtain J
syms Qs Q1 Q1T n
b = [1; 0.18];
Qs = [1.2191-2.16645*n -1.09875+1.0339*n; -11.11*n -6.25];
Q1 = inv(Qs);
Q1T = Q1.';
J = (1+n^2)*b'*Q1T*Q1*b;
```

```
% obtain J against n plot
figure,
subplot(2,1,1), ezplot(J), ylabel('J'), title('Performance Index'), grid
subplot(2,1,2), ezplot(J,[-0.1 0.02]), ylabel('J'), grid
title('Performance Index with a localized range of n')
% minimize
jfun = matlabFunction(J);
n0 = 0.1;
opts = optimset('TolX', eps);
[nmin, jmin] = fminsearch(jfun, n0, opts);

% Obtain Q
Q = feval(matlabFunction(Qs), nmin);

% obtain h
k1 = 1;
h = (Q\b/k1)';
h0 = h;

% obtain k
k = [k1; k1*nmin];

% obtain K(s)
R = 1;
K = k*R;
K0 = K;

% outer loop
Ss = [1 0.01; 0.01 1];
fun = @(fs) [fs 0; 0 fs];
f= [0.1 0.3 0.65 0.85];
% f = 0.85;
model = 'lec_model.mdl';
for index = 1:length(f)
    fs = f(index);
    F = fun(fs);
    % feed forward gain
    P = (G0^-1 + kron(h0,K0))*Ss*(eye(2)-F*Ss)^-1;
    % feedback gain
    H = P^-1*kron(h,K) + F;

    % simulate
    % cases
    % Case 1: v1 = 1, v2 = 0, d1 = 0, d2 = 0
    V = [1 0];
    d = [0 0];
    sim(model)
    t = ScopeData.time;
    x1 = ScopeData.signals(1).values;
    x2 = ScopeData.signals(2).values;
    figure, plot(t, [x1, x2], 'LineWidth', 1)
    xlabel('Times [s]'), ylabel('\theta [rad]'), legend('\theta_1', ...
        '\theta_2');
    title('v_1(t) = 1, v_2(t) = 0, \delta_1(t) = 0, \delta_2(t) = 0')
    % Case 2: v1 = 0, v2 = 1, d1 = 0, d2 = 0
    V = [0 1];
```

```
    sim(model)
    t = ScopeData.time;
    x1 = ScopeData.signals(1).values;
    x2 = ScopeData.signals(2).values;
    figure, plot(t, [x1, x2], 'LineWidth', 1)
    xlabel('Times [s]'), ylabel('\theta [rad]'), legend('\theta_1', ...
        '\theta_2');
    title('v_1(t) = 0, v_2(t) = 1, \delta_1(t) = 0,\delta_2(t) = 0')
    % Case 1: v1 = 0, v2 = 0, d1 = 1, d2 = 0
    V = [0 0];
    d = [1 0];
    sim(model)
    t = ScopeData.time;
    x1 = ScopeData.signals(1).values;
    x2 = ScopeData.signals(2).values;
    figure, plot(t, [x1, x2], 'LineWidth', 1)
    xlabel('Times [s]'), ylabel('\theta [rad]'), legend('\theta_1', ...
        '\theta_2');
    title('v_1(t) = 0, v_2(t) = 0, \delta_1(t) = 1, \delta_2(t) = 0')
    % Case 1: v1 = 0, v2 = 0, d1 = 0, d2 = 1
    d = [0 1];
    sim(model)
    t = ScopeData.time;
    x1 = ScopeData.signals(1).values;
    x2 = ScopeData.signals(2).values;
    figure, plot(t, [x1, x2], 'LineWidth', 1)
    xlabel('Times [s]'), ylabel('\theta [rad]'), legend('\theta_1', ...
        '\theta_2');
    title('v_1(t) = 0, v_2(t) = 0, \delta_1(t) = 0, \delta_2(t) = 1')
end


% with all inputs set
fs = 0.75;
F = fun(fs);
% feed forward gain
P = (G0^-1 + kron(h0,K0))*Ss*(eye(2)-F*Ss)^-1;
% feedback gain
H = P^-1*kron(h,K) + F;

% simulate
% Case: v1 = 1, v2 = 1, d1 = 1, d2 = 1
V = [1 1];
d = [1 1];
sim(model)
t = ScopeData.time;
x1 = ScopeData.signals(1).values;
x2 = ScopeData.signals(2).values;
figure, plot(t, [x1, x2], 'LineWidth', 1)
xlabel('Times [s]'), ylabel('\theta [rad]'), legend('\theta_1', ...
    '\theta_2');
title('v_1(t) = 1, v_2(t) = 1, \delta_1(t) = 1, \delta_2(t) = 1')
% simulate open loop with all inputs active
model = 'open_loop.mdl';
% cases
% Case 1: v1 = 1, v2 = 1, d1 = 1, d2 = 1
```

```
V = [1 1];
d = [1 1];
sim(model)
ScopeData
t = ScopeData.time;
x1 = ScopeData.signals(1).values;
x2 = ScopeData.signals(2).values;
figure, plot(t, [x1, x2], 'LineWidth', 1)
xlabel('Times [s]'), ylabel('\theta [rad]'), legend('\theta_1', ...
    '\theta_2');
set(gca,'xlim',[0 50])
```

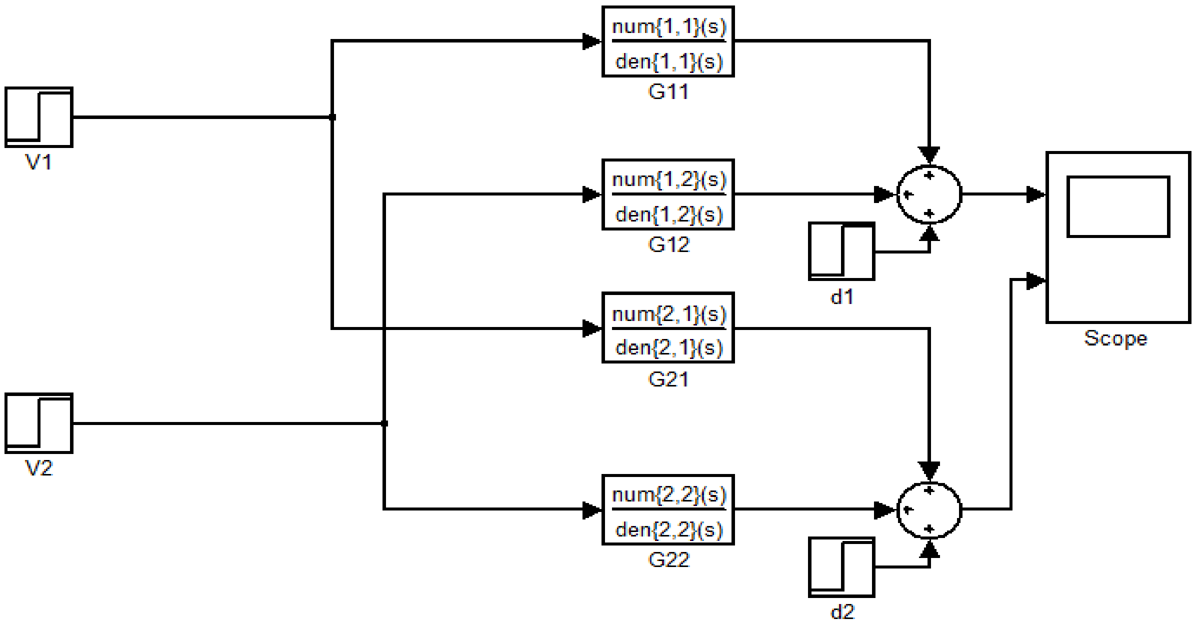

Figure A.1: Open Loop System Model

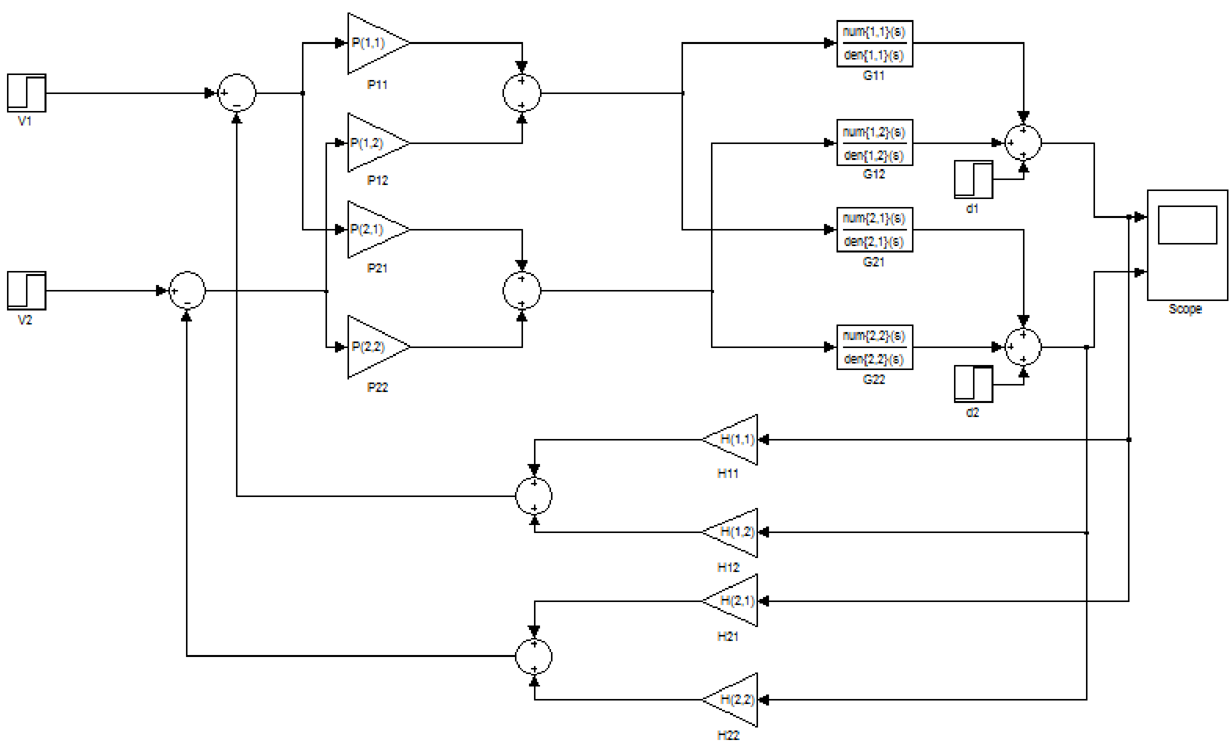

Figure A.2: Least Effort Controller Model