OPTIMIZATION MODEL FOR THE POWER SUPPLY OF OFFSHORE OIL AND GAS PLATFORMS

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ELECTRICAL ENGINEERING

MAY 2018

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

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Dedicated to the souls of my father and grandmother

ACKNOWLEDGMENTS

Acknowledgment is due to the King Fahad University for Petroleum and Minerals and Electrical Engineering Department for supporting this research.

I would like to express my sincere gratitude and appreciation to my advisor and mentor Dr. Ibrahim El-Amin for his guidance and encouragement since the day one of starting the degree.

I extend my gratitude to Dr. Mohammad Al-Muhaini and Dr. Ali Al-Awami for their advice and constructive feedbacks.

My sincere thanks also go to my friend Fahad Al-Otaibi for the uncountable discussions and feedbacks that added value to the thesis.

I would like to express my thanks to my brothers and sister for their motivation and concern.

Last, but not least, a special thanks to the greatest women in the world, my mother for her continued support, encouragement and endless prayers that light my life.

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NOMENCLATURE

ABBREVIATIONS

BLX-α	:	Blend Crossover
BN	:	Bayesian Network
CapEx	:	Capital Expenditure
CDP	:	Conditional Distribution Probability
CNSE	:	Cost of Non-Served Energy
CO2	:	Carbon Dioxide
DFIG	:	Doubly-Fed Induction Generator
DG	:	Distributed Generator
ED	:	Euclidian Distance
ENTSOE	:	European Network Transmission System Operator for Electricity
FOR	:	Force Outage Rate
GA	:	Genetic Algorithm
GOSP	:	Gas Oil Separation Plant
HVAC	:	High Voltage Alternative Current
HVDC	:	High Voltage Direct Current
IEC	:	International Electrotechnical Commission
IEEE	:	Institute of Electronics and Electrical Engineers
IGBT	:	Insulated Gate Bipolar Transistor
JPD	:	Joint Probability Distribution
LCC	:	Line Commutated Current
LCOE	:	Levelized Cost of Energy
LFAC	:	Low Frequency Alternative Current
LGS	:	Local Generator Set
LOLD	:	Loss of Load Duration
LOLF	:	Loss of Load Frequency

LOLP	:	Loss of Load Probability
MDP	:	Marginal Distribution Probability
MST	:	Minimal Spanning Tree
MTS	:	Minimum Tie Set
NREL	:	National Renewable Energy Laboratory
OpEx	:	Operational Expenditure
PDF	:	Probability Density Function
PMSG	:	Permanent Magnet Synchronous
PWM	:	Pulse Width Modulation
RBTS	:	Roy Billinton Test System
REM	:	Reference Electrification Model
SCIG	:	Squirrel Cage Induction Generator
STATCOM	:	Static Synchronous Compensator
TL	:	Transmission Line
UI	:	User Interface
VSC	:	Voltage Source Converter
XLPE	:	Cross-linked polyethylene

SYMBOLS

P_{loss}	:	Power Loss in W
TL^n	:	Number of Transmission Line Cables
TL^{Tech}	:	Transmission Line Technology
TL^V	:	Transmission Line Voltage in Volt
A	:	Cross section Area of the Cable in mm^2
$CostGen$	:	Total Generation Cost is USD
$CostGG$	:	Total Gas Generator Cost in USD
$CostSystem$	:	Total System Cost in USD
$CostWT$	:	Total Wind Turbines Cost in USD
D	:	Distance Matrix in km
EC	:	Yearly Energy Consumption in kWh
ED	:	Euclidian Distance in km
GC	:	Grid Connection State Random Variable
GE	:	Yearly Energy Purchased from the Onshore Grid
GG	:	Gas Generator Power State Random Variable
GGE	:	Yearly Energy Generated by Gas Generators in kWh
GP	:	Gas Generator Power Capacity in MW
LD	:	Load Demand in MW
LGS	:	Local Generation Set State Random Variable
LOL	:	Loss of Load Probability Distribution
$LOLD$	:	Loss of Load Duration
$LOLF$	:	Loss of Load Frequency
$LOLP$	:	Loss of Load Probability
LP	:	Installed Load State Random Variable
MTS	:	Minimum Tie Set State Random Variable
$MTTF$	:	Mean Time to Fail in year/ failure
$MTTR$	:	Main Time to Repair in hours

PWF	:	Present Worth Factor
Qc	:	Capacitive Reactive Power in Var
Ql	:	Inductive Reactive Power in Var
Qt	:	Total Reactive Power in Var
TL	:	Transmission Line State Random Variable
TLC	:	Transmission Line Thermal Capacity in MW
$TLCost$	:	Transmission Line Cost in USD
ToD	:	Time of Day State Random Variable
ToY	:	Time of Year State Random Variable
V	:	Velocity of wind Speed in m/s
WE	:	Yearly Energy Generated by Wind Turbines in kWh
WG	:	Wind Power Random State Variable
WP	:	Wind Turbine Power Capacity in MW
WS	:	Hourly Wind Data State Random Variable
λ	:	Failure Rate in fail/ year
μ	:	Repair Rate in repair/ year

ABSTRACT

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Title: Optimization Model for the Power Supply of Offshore Oil and Gas Platforms

Degree: Master of Science

Major Field: Electrical Engineering

Date of Degree: May 2018

The thesis aims to study the power supply problem of offshore loads related to oil and gas industry using different technologies including renewable resources. An optimization model is proposed to solve the power supply problem with two main objectives: maximizing reliability and cost effectiveness of the power supply. To cover the offshore platform power supply problem, the thesis will discuss the following topics:

- Comparison between using onshore connected power supply and standalone system
- Feasibility of using HVAC or HVDC transmission systems to supply offshore loads
- Integrating Wind energy to supply the offshore platform as alternative power supply

Models will be developed to evaluate the load requirement and asses the system reliability. The effect of the developed method on existing installation will be evaluated. Finally, recommendations will be delivered based on the advantages and disadvantages of applying the proposed model in term of reliability, cost-effectiveness, operation, and environment.

ABSTRACT (ARABIC)

ملخص الرسالة

الاسم: مهند مسعود آل خريجه

عنوان الرسالة: بناء نموذج لإيجاد الحل الأمثل لتوصيل الكهرباء لمنصات النفط والغاز البحرية

الدرجة: ماجستير في العلوم

التخصص: الهندسية الكهربائية

تاريخ التخرج: شعبان ١٤٣٩

يهدف البحث إلى دراسة توصل الكهرباء للأحمال الواقعة في المحيطات والبحار (الأحمال البحرية)، وبالخصوص تلك المتعلقة باستخراج الغاز والنفط من عمق البحار. تتركز هذه الدراسة في البحث عن أفضل السبل لتوصيل الكهرباء باستخدام طرق مختلفة عن الطرق التقليدية كاستخدام التيار المتواصل بدل التيار المتردد وكذلك استخدام الطاقة المتجددة كطاقة الرياح لتوفير الكهرباء لتلك الأحمال. للوصول إلى الهدف الرئيسي للدراسة سيتم تطوير نموذج تقوم بعملية بحث موضوعي عن أفضل حل ممكن من حيث التكلفة الكاملة وموثوقية النظام، وسيتم البحث عن الحل الأمثل باستخدام النموذج المطور للوصول إلى ملخص وتوصيات مفندة تتطرق للمواضيع التالية:

- مقارنة استخدام نظام متصل بالشبكة المحلية أو استخدام نظام منعزل لإنتاج الكهرباء
- مقارنة الجدوى الاقتصادية بين استخدام التيار المتردد مقابل التيار المستمر لتوصيل الكهرباء للأحمال المائية
- الجدوى الاقتصادية من استخدام طاقة الرياح كمصدر للطاقة النظيفة للأحمال المائية

خلال الدراسة سيتم تطوير نماذج لتقييم متطلبات الأحمال الكهربائية وحساب التكلفة الكاملة للنظام وتقييم الموثوقية. وسيتم تطبيق الدراسة على أنظمة مبنية مسبقا وأنظمة جديدة لمعرفة تأثيرها على النظاميين. وختاما سيتم تقييم الدراسة المطروحة والتطرق لإيجابيات وسلبيات استخدامها على أنظمة مبنية مسبقا وأنظمة مستحدثة من حيث الموثوقية، والتكلفة، وطبيعة التشغيل، وتأثيرها على البيئة.

CHAPTER I

INTRODUCTION

1.1. Overview

The power demand of offshore loads such as oil and gas platforms possesses high potential area of improvement. Typically, offshore platforms are scattered in large sea area and required high reliability supply due to operation nature and cost of outages. Currently, most of the platform loads use fossil fuel-based generators which require continues fuel supply and has reliability concerns. There are operating issues related to motor starting and stability. Moreover, the financial cost of operating and maintaining fossil fuel-based power supply is high comparing to using onshore energy source [1][2].

Using onshore power supply as an alternative is gaining large attention recently due to many reasons, most importantly reliability of the power source and financial and environmental reasons. However, the conventional transmission lines use High Voltage Alternative Current (HVAC) which has some limitation when using submarine systems over long distances. The conventional HVAC transmission system proved to be unfeasible solution to supply offshore loads and is fairly expensive in many cases especially for long distance [3][4]. Recently, new trends appear with promising features, such as High Voltage Direct Current (HVDC) which has no limitation regarding the distance with submarine transmission system. Additionally, with the development of power electronics especially Voltage Source Converter technology, HVDC is an attractive solution to transmit power over the offshore. The advantages of HVDC are not limited to the mentioned points only, it also provides controllable load flow, more flexible connection and less short circuit contribution compared to HVAC [5].

Another appropriate option is using isolated grid. In fact, in the recent years, there is huge movement towered having independent microgrids that can operate using Distributed Generators (DG). The main derive to this movement is the introduction of renewable energy generation. Considering DG in the mixture will add many levels of complexity to achieve optimum decisions. A wind farm is attractive for offshore installation since it will have higher and high consistent wind speed compared to onshore wind farms [2]. Many publications observe the potential of integrating wind energy to supply offshore installation. The studies cover many aspects of using wind energy to electrify offshore installation including economic value, environmental impact, and operation issues such as the power system stability [7] – [12].

1.2. Thesis Objective

The objective of this thesis is to develop a model that searches for the optimum power supply plan of offshore loads in term of cost-effectiveness and the reliability of the power supply. The outcome of the model includes the transmission line topology, transmission line technology, and distributed generation technology including renewable resources. Additionally, the performance of the proposed model is displayed to show the value of the proposed solution.
To achieve this objective, an optimization algorithm will be developed to find the optimum solution. The selection of the solution depends on two factors: the cost of the system and reliability of the system. The algorithm will include a mechanism to account for the tradeoff between those two conflicting objectives. Moreover, a cost model will be developed to estimate the cost of any system in the search space. Similarly, a mathematical model will be developed to calculate reliability indices. The final output of the proposed model is a set of solutions that satisfy the optimization requirements. Then, the performance of those solutions will be evaluated in term of their cost, reliability, design, and technology. This information can be used to select the solution that fits the situation, which might differ from case to case.

1.3. Thesis Contribution

The main contribution of this thesis can be summarized in the following points:

A) Develop an algorithm to find and design the optimum power supply plan for offshore oil and gas platforms considering the cost and reliability of the power system. The output of the algorithm includes the selection of the power supply in term of connecting the platforms to the onshore grid or not, transmission line technology and design, and Distributed Generation technologies and capacity.

B) Develop a new model for reliability assessment using Bayesian Network. The proposed model will calculate the reliability of microgrids and incorporate the power connection topology, distributed generation states and active loads.

1.4. Thesis Structure

The thesis organized the following: In chapter 2, a literature review is shown to explore the similar researches and tools and previously published work. Chapter 3 shows a technical review of the systems and components that are considered in the technology search space. In chapter 4, the cost model is illustrated in details. The component cost and their parameters are shown in this chapter. Chapter 5 shows the reliability assessment model that will be used to quantify the system reliability. In chapter 6, an algorithm is proposed to find the optimum location of a common bus. In chapter 7, the proposed algorithm is explained in details. The reliability assessment model, cost model, and all other mathematical techniques will be used to build the algorithm. The overall model and the workflow of the implementation are shown in this chapter. In chapter 8, the proposed model will be tested and verified by applying it to several case studies. The implementation process and how to use the proposed model explained in details. The results of the implementation are discussed in details with highlighting major findings and comments. Finally, in chapter 9 a summary and future work are presented.

CHAPTER II

LITERATURE REVIEW

2.1. Oil and Gas Platforms

The oil and gas exploitation started back in the second half of the nineteenth century while offshore oil and gas extraction considered started approximately in the last forty years. Due to this fact many offshore fields still expected to be explored in the coming years. Moreover, many of offshore fields are already identified but the operation still not started and expected to be planned in the next 30 years depends on many factors. The offshore fields still not fully utilized yet, which means there are opportunities to increase the reserves of existing fields. The future oil and gas exploration will be oriented toward offshore fields since it provides attractive investment and many areas are not discovered. The development of oil and gas field is directly dependents the oil price which affected by political and economic factors [13].

One of the major concern of operating offshore platform is the power supply. There are many challenges that encounter oil and gas companies to electrify the offshore load. Those challenges and technical details have been discussed in [14]. The offshore electrical system has many special requirements. It is usually scattered in far offshore locations from onshore making it challenging to connect it to shore substations. Due to high investment cost and operation nature, special power supply characteristics are required [15].

The reliability and availability of the power source are major considerations to operate the electric loads that include drilling, exporting and injection machine in addition to the auxiliary loads. Any power outage could lead to large production loss.

Currently, most of the platforms are fed from onsite fossil fuel-based generators [6]. The major loads of an offshore platform are pumps operated by either synchronous or induction motors. The single platform usually has a load of 8-20 MW [6]. Platforms usually are located close to many other platforms within the same field. The load at one site could reach up to 530MW which requires a large amount of generation units. During the lifespan of the oil and gas

platform, additional motors are installed to increase the field pressure. This leads to the need for additional power supply to be planned [3].
The oil field typically consists of main platforms or Gas Oil Separation Plant (GOSP) and connected to many platforms. The planning process focuses on delivering the power to the main platform and assume the other platform connections are considered at different planning stages. The GOSP unit usually contains the processing and transportation machines in addition to the power generators or onshore connections. While the other platforms contain the drilling wellheads and injection motors [15].
In general, the power generation for the offshore platform is divided into three categories:

- Primary Power Supply
- Emergency Power Supply
- Essential Power Supply

The primary power source is the one to supply all electrical loads during normal operation. This power source must be reliable and efficient to ensure continuous operation of the platforms. Distributed generation units or submarine cable systems from onshore substation can be considered as a main power source. Optimization planning for the main power source is a major factor for operation offshore platform and has a considerable impact on the overall cost of the project. The focus of this thesis will be headed to optimize the main power source.
The emergency power source is designed to operate when the main power supply is unavailable due to any reason. Usually, it is provided by diesel generator independent from the main power source. It supplies firefighting equipment, critical life support utilities and other essential loads. The size of the emergency generator could vary depending on the platform load from 0.5 to 2 MW [6]. The emergency power generation is not considered as a be part of the study since it's mandatory.
The last type of power generation is the essential power generation. The purpose of this power source is to start the main operation equipment or sometimes during the commissioning of a new platform. It also provides a black start function for the platform. Similar to the emergency this power supply usually provided by diesel engine independent of the main source. The existing of this category is not mandated and it doesn't exist on all platforms [16] [17]. The essential power source will not be included in this study for the simplicity purposes.

2.2. The Supply Problem

The need to solve the electrification and supply problem goes back since the beginning of the power system era. The question was either to use AC or DC to deliver power to houses. This issue appears again in the recent years with more complexity. The new trends associated with the electrification is due to the introduction of renewable energy as an available option and the advancement of power electronics. This raises the number of researches on power supply problem, especially for rural area and isolated grids [18]. There are several tools proposed to address the electrification problem. A tool called Network Planner try to solve the electrification problem to interconnect remote rural loads with a wide range of options [19] [20]. The tool firstly published in 2014 by Modi Research Group and Columbia University and has an online interface website. This tool focuses mainly on the economic aspect of the problem and allows the user to explore the most cost-effective technologies to a specific condition.

Another tool developed by Universal Access Lab at Massachusetts Institute of Technology and IIT-Comillas University called Reference Electrification Model (REM) [21] [22]. The main purpose of the tool is to find the optimum electrification plan for rural areas. New technique is proposed to solve the problem considering the technology design and quality of service. Both tools provide a reliable solution for the intended purpose of rural area electrification with more technical details in REM. However, REM doesn't consider the reliability of the interconnection. The authors look at the problem from supply demand point view in a deterministic way. Moreover, both tools are designed for low and medium voltage power systems. There is no consideration for long distance and high voltage application [18] [21] [22].

Another popular tool provides a solution for electrification of a microgrid with renewable energy integration called HOMOR Energy. Several publications observed in the literature utilize HOMER Energy for optimization and investigation of microgrids. The tool developed by National Renewable Energy Laboratory (NREL) and has been commercialized in 2009. The tool provides great insight into the proposed system with a mature graphical interface to investigate different selections. However, the tool doesn't consider the transmission line and interconnection optimization. The tool designed to optimize the resources of single bus considering different distributed generation technology and either to have off-grid or on-grid option with predefined cost [23] [24].

Finally, a research discusses the environmental impact of offshore installation electrification in the Norwegian continental shelf [25]. A Net Transfer Capacity model is used to model the power system and calculate the system feasibility with the inclusion of carbon emission taxes in the calculation. The study shows how the selection criteria of the optimum electrification plan will vary depending on the applied taxes value of CO^2 emission footprint. The nodel estimates the cost increment of the electrification due to the emission cost incorporation and how it might change the optimum solution [25].

2.3. Offshore HVDC Transmission Technology

The advancement of the power electronic devices and control technologies led to vast enhancement of HVDC technology. The higher switching rate and lower loss of power electronics make the HVDC more mature and provide many attractive advantages. The size of converter station became more compact making it suitable for limited areas like offshore platforms. In addition to the size requirements, using advanced control techniques allow for power flow controllability of HVDC systems [26]. The control techniques also provide the possibility of connecting Multi-Terminal HVDC system which will lead to more flexible and suitable solution for offshore platforms in term of future expansion opportunities. DC power system has no skin effect issue and no charging current caused by the submarine cable insulation which leads to large cost reduction in the investment [27]. Moreover, the Voltage Source Converter (VSC) based HVDC systems are capable of supplying both active and reactive power which clearly leads to the improvement of the system stability [4]. Due to the nature of the offshore environment and accessibility limits, the installation costs play a major rule in planning for such a system. Cost reduction could be achieved by introducing Multi-Terminal HVDC transmission system and integrating DC bus with the offshore load in an intermediate location to reduce the installation cost [28].

2.4. Offshore Windfarm

In the recent years, the interest is growing toward using wind energy as a renewable power source due to many reasons. Large projects around the world have been constructed or planned to integrate wind farms especially in offshore location [1]. Data collected from existing systems show that the capacity factor of offshore wind farms could be between 40 to 50% compared to

25 to 35% in case of onshore wind farm [28]. Another advantage of offshore wind farms is the less environmental and visual impact compared to onshore systems. Many challenges are raised with integrating offshore large wind farms from planning, design, construction, and operation of such a system.

An important factor is the maximum allowable energy delivered by the wind energy [8]. The design of the wind system must consider the case where there is no wind speed at all and the output power of wind turbine is zero. On the other hand, there is a maximum limit of the power generated from the wind farm. Moreover, the existing of the wind energy generators as a power supply enhances the availability by reducing the restoration time [7].

To be able to determine the power supply rating, losses, and reliability a stochastic model for the power system need to be developed. Many publications use a steady state load flow with rating power values of the load and wind turbine and with no power output of the wind turbine to estimate the power flow and hence estimate the power losses and cable sizing [15]. It's worth to mention that installing the wind farm close to the load center has a huge impact on the power losses. In many publications [29] [30] the Weibull or Rayleigh distributions are used to calculate the wind farm output energy a function of the wind speed occurrence. Hence the current profile and power losses and cable rating can be calculated. Another technique used on [9] called Quasi Steady State model. Where the model doesn't consider the stochastic behavior of the energy flow. In this case, one-year simulation is conducted to evaluate the reliability of the purposed system.

2.5. Reliability Assessment with Renewable Resources

The offshore loads require reliable power supply. In the recent years, new trends appear to the power system that can be utilized for offshore power system. One of the major trends is having many distribution generators especially renewable sources. This will lead to having bidirectional flow of energy from the load to the grid [31]. This advancement is supposed to raise security level, enhance the reliability, and reduce the operation cost of the power system by increasing the efficiency. However, this added many levels of complication especially with the uncertainties associated with renewable sources. These uncertainties complicate the reliability assessment process and require advanced reliability assessment techniques to measure reliability indices and overcome the complexity of the new power systems.

Many techniques have been proposed to assess the reliability of power system considering the uncertainty with renewable energy [31] – [35]. The challenge with the renewable energy is to consider many states with varying probability depending on the nature of the source and the state of the generators. Models have been developed to assess the reliability of renewable generator, in [32] a model is developed for wind turbine considering both the wind speed variability and force outage rate of the generators using Monte Carlo Simulation. Reference [36] investigates the enhancement of the reliability of power system if new renewable resources are added to an isolated grid and the problem is solved in a deterministic manner by calculating the demand and supply balance.

A machine learning based technique called Bayesian Network (BN) receives large attention from researchers from different fields including reliability assessment. It provides a convenient way to represent all the state of the power system component and compute the loss of load probability efficiently. Moreover, analyzing the system is much easier when a certain state of any component is known by using inference technique. Moreover, it provides a stochastic representation of the supply availability and load demand at any point in the system that can be associated with certain time. The other advantages of BN model for power system reliability assessment that make it attractive as shown in [37]:

- Its simplicity and similarity to the physical topology of the power network, which provides an intuitive way to visualize and understand the reliability of the power system.
- It can implement multi-state components and their correlation with each other including the uncertainty of any component.
- It investigates specific failure mode and conduct what-if analysis and identifies the most probable cause.

There are several BN models that have been utilized in a wide range of applications including reliability assessment of power system [37] – [39]. In [37] a BN reliability assessment model is proposed with large multi-area network and it’s not applicable for the distribution network. Another paper [38] propose BN for distribution network but without considering the reliability of the transmission lines. A BN is proposed in [39] where the authors consider composite reliability assessment suitable for the distributed network but they didn’t consider the stochastic behavior of the loads and DG's. The authors assume the load and generators are constant and don't vary with time.

2.6. Research Gaps

There are different approaches to solve the power supply problem. Each of them is developed to serve specific purposes for certain application. Those techniques could lead to different solutions with variation in the proposed technologies, the components size and the power supply reliability. Most of the power supply optimization solutions focus on delivering the power to the loads in rural areas. The reliability assessment aspect is either missing [19] or limited [18]. The proposed solutions in [18] – [22] are always radial configuration. The algorithm is not designed to consider loop or meshed connection, even if there are constraints or tradeoff value for reliability.

A reliable power source is required for offshore installation as discussed in [14]. The attention is increased to have a reliable and cost-effective power supply. Moreover, several new technologies have been suggested to electrify offshore installation rather than the conventional solution. Those techniques include using HVDC transmission systems and utilizing wind energy. This thesis is addressing the offshore power system problem considering the reliability and the cost of the power supply.

CHAPTER III

TECHNICAL REVIEW

Many alternatives exist to supply offshore power system. Each of them has its own pros and cons in term of cost-effectiveness, complexity, reliability and their environmental impact. In this chapter, a technical overview is presented.

3.1. Transmission System

Transmission system provides a great solution to supply the offshore platforms. Generally speaking, the cost of power generated from an onshore grid is much cheaper than offshore generations. However, the cost of installing transmission system will increase the capital cost. On the other hand, the operation cost of a transmission system is expected to be lower compared to offshore generation solution. Two options for the transmission system exist HVAC and HVDC. Each technology has its own pros and const. For example, HVAC provides cheaper installation cost but it required reactive power compensation when it is installed for long distance. While the HVDC is an attractive solution for long distance but it is more complex and has higher installation cost [40].

3.1.1. HVAC Transmission Systems

HVAC is the most common technology used for the commercial offshore grids until today. It's widely used due to its maturity level, simplicity and the existing expertise at the utilities [41]. In the HVAC system, the cables are connected to a substation where the voltage is increased to be transmitted with lower losses. The power is transmitted through buried submarine cables to the onshore substation.

The main constraint of the HVAC system is due to charging current. The charging current is induced due to the capacitance of the submarine cable. [42]. The amount of the charging current is proportional to the cable length and the voltage level. In some cases, it's not adequate to install compensation at the ends of the transmission line, and a mid-route compensation is required. It is not feasible to install compensation at the mid-route as it will require additional offshore platforms.

3.1.2. HVDC Transmission Systems

HVDC transmission systems gained large attention since the early 70's due to the development of power electronics devices. The fact the DC system is not oscillating and doesn't produce reactive power in steady state operation. That will allow utilizing the actual ampacity of the cable without the need to having reactive compensation. Furthermore, the limitation on the transmission line length is ideally doesn't exist. Moreover, the skin and proximity effect affect the ampacity and resistance of the cables in HVAC system, while in HVDC those two effects are eliminated. The basic operation of HVAC system to transmit the power to offshore as following: the cable is collected from the network in power substation. The voltage is then increased and converted to DC to transmitted. Similar to HVAC system the cables are buried or laid down at the sea floor and connected to the onshore substation. Then the current is converted back to AC to be connected the grid [40] – [41].

3.1.3. Comparing Current Source vs Voltage Source Converters

There are two main converter technologies are used commercially. Currently, the most common technology in operation is the Current Source Converters or what is known Line-Commutated Current (LCC). This first known project that uses LCC was commissioned in 1954 to connect the Swedish grid with an island of Gotland [40]. Since then, there were many projects was constructed with LCC technology to utilize the advantages of HVDC system. This technology uses thyristor to convert the current which can only turn off when the current goes to zero. LCC HVDC system requires an AC grid that operates with voltage and frequency to enable the commutation process and turn the converters. Reactive power is required to operate the LCC converter. The LCC HVDC system can be operated in two directions, however, to reverse the current direction, the voltage needs to be reversed which is a time-consuming process.

Voltage Source Converter (VSC) HVDC Systems has been on the market for many years. It was used mainly for low power application such as motor drives etc. The first power transmission project using VSC HVDC system was commissioned in 1997 with 3 MW power capacity. Since then, the technology proved its feasibility and it has been installed in many projects [41]. VSCs uses Insulated Gate Bipolar Transistor (IGBT) which allow controlling the switch on and off process using Pulse Width Modulation (PWM) based controllers. Unlike the LCC, the VSC can be operated without the need of operating grid to transmit power. The main advantage of VSC over the LCC is the Black Start capability and can be operated even with weak AC grid. Moreover, controlling the on and off switching time increases the controllability of the power flow to and from the grid. A qualitative comparison between the HVAC, VSC and LCC HVDC systems is summarized in Table 3.1 [40] [41] [44].

Table 3.1: Comparing Three Transmission Line Technologies

Description	HVAC	LCC HVDC	VSC HVDC
Voltage Level	Up to 245 kV	Up to ±450 kV	Up to ±300 kV
Volume	Small	Large	Medium
Substation Cost	Low	High	Very High
Substation Power Loss	Low	Medium	High
Cable Power Loss	High	Low	Low
Complexity	Low	High	High
Experience	Mature	Mature	New Technology
Power Flow Reversal	Fast	Low	Fast
Black Start Capability	Exist	Not Exist	Exist
Compensation	Required	Required	Not Required
Ride Through Capability	Not Exist	Not Exist	Exist
Harmonics	None	High	Low

VSC HVDC provides an attractive solution for offshore applications. Although the cost of VSC is higher than LCC technology, the required area and the other adventives justify the high cost. Moreover, the HVAC solution still an attractive solution for short distances with low power consumption. The important question to be asked is which technology to use for each specific application. In this thesis, only two technologies are considered HVAC and VSC HVDC.

3.2. Submarine Cable

Submarine cables are required to transmit the power from and to offshore platformer. Generally, HVDC and HVAC transmission systems can use same cable technology. The main difference of the cable technology is the insulation material and method [44]. Recently, the most common dialectic material used for underground and submarine cables is Cross-Linked Polyethylene (XLPE). Figure 3.1 shows cross-section example of typical XLPE submarine cable [44]. Although there are many technologies of cables such as Mass Impregnated Paper, the XLPE cables provide many adventives over the other technologies and it's widely used for bulk power transmission. It has high continued and short circuit capacity due to its thermal characteristics. The insulation loss is much less than other technologies, considered environmentally friendly and maintenance-free [41].

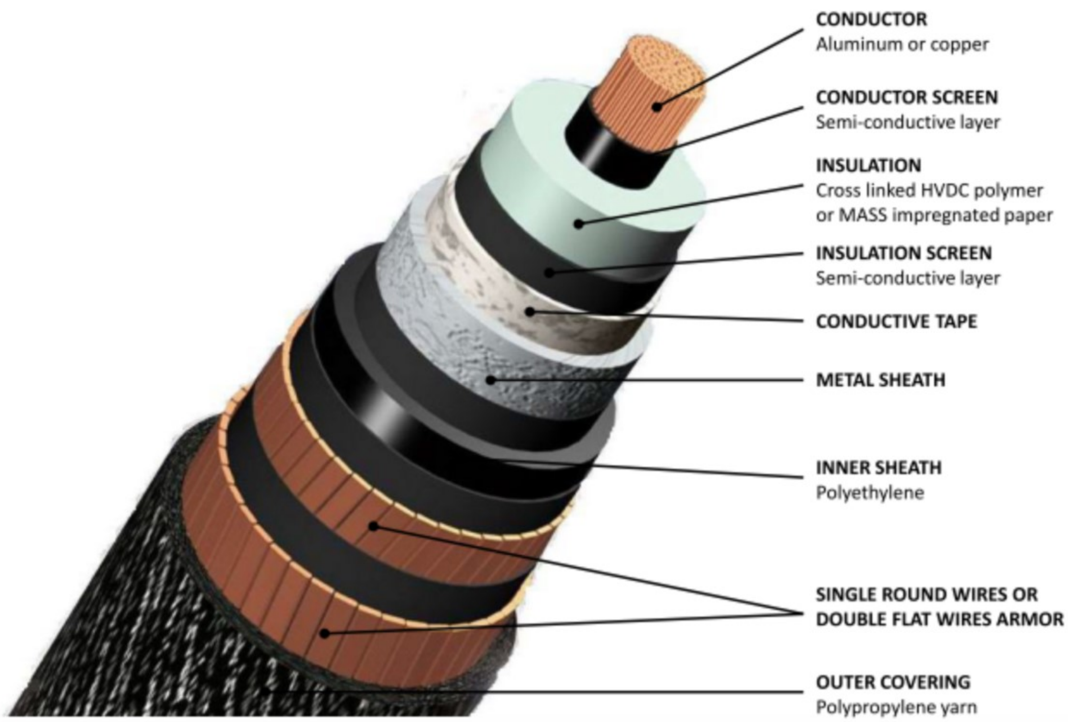

Figure 3.1: XLPE Submarine Cable Components [44]

Tables A.1 and A.2 in Appendix A show typical values of submarine XLPE cables obtained from [45] and cable datasheet [46] – [49]. Some of the values are not incorporated in the references and to have continuous values for all cables sizes a linear regression is used to fill those missing values such as the ampacity of cables with 95 and 800 mm^2. The reactive power requirement of submarine cable can be calculated using equations 3.1 – 3.3.

$$Qc = n\,3\left(\frac{V}{\sqrt{3}}\right)^2 2\pi\, f\, C \tag{3.1}$$

$$Ql = n\,3\,I^2\, 2\pi\, f\, L \tag{3.2}$$

$$Qt = Ql - Qc \tag{3.3}$$

where Qc and Ql are the capacitive and inductive reactive power measured in Var, respectability. Qt is the resultant reactive power in Var. V and I are the rating RMS Voltage and Current measured in volt and ampere, respectively. f is the frequency in Hz (in this case is 60 Hz). C is capacitance measured in Farad. L is the inductance measured in Henry. n is the number of cables installed in parallel.

3.3. Distributed Generators

Another option to supply the offshore platforms is to install local generation at the site. Many platforms are operated by distributed generations. Due to the gas availability at the, most of those generators are fueled by natural gas. Another interesting technology that aligns with the government directions towered renewable energy is the wind farms. It can provide a great solution, especially since the offshore wind farms have more power factors and is preferred for offshore installation. In this thesis, two technologies are considered to supply offshore platforms, namely gas generators and wind turbines.

3.3.1. Gas Generator

Most of the platforms are either connected to the grid or operated by gas generators. It provides great solution due to its cheap capital cost, easy to maintained and the availability of the natural gas at the offshore platforms. Moreover, the gas generations can support large-scale offshore installation up to 50 MW with a compact size suitable for offshore installation. In the other side, the main disadvantage of the gas generator is the operation cost, which includes the maintenance and fuel cost. The conventional gas turbine operates using natural gas engine associated with simple cycle electric generators. The gas generator provides fast response to meet the demand, which makes suitable for islanded networks. The starting time is also minimal, around one minute, makes it an ideal solution as a back-up to ensure continuous operation. Moreover, it can operate with low power factor and provide reactive power for installed motors. The efficiency of the gas generator is measured by the heat rate of the gas turbine and the efficiency of the electrical generator. A typical heat rate of gas turbine reported in [51] to be equal to 9,800 Btu/kWh or 10340 kJ/kWh. That number could vary depends on the machine design and manufacturer specification. For example, a gas engine manufactured by Rolls Royce has a heat rate equal to 7500 kJ/kWh as reported in the machine datasheet [52].

3.3.2. Wind Turbine

Renewable energy gains large attention in the last decade to cope with the increased demand worldwide. The penetration of the wind is growing rapidly with estimated of 540,000 GW installed capacity at the end of 2017. About 19,000 GW of wind farms are installed offshore. Figure 3.2 shows the communitive installed capacity of offshore wind turbines worldwide [53]. The main advantage is the wind condition at the offshore is better than onshore in term of consistent wind speed and less turbulence due to the smooth surface of the sea. The average capacity factor of the offshore wind turbine could go up to 50% compared to 25% of onshore [40]. Wind systems industry faces huge concerns in some countries as they cause visual and noise pollution [54] [55]. On the other side, the main disadvantage of offshore installation is the cost associated with the foundation construction and transmission line. However, since the proposed location of the wind turbines in this thesis is close to oil and gas platforms, the contribution of the transmission lines cost will be included in the overall cost of the project. That could make it a feasible option to supply offshore installation.

The output power of the wind turbines is proportional to the cube of the wind speed. Equation 3.4 shows the basic equation of the output power as a function of the wind speed [29].

$$P_{Wind\ Turbine} = \frac{1}{2}\ C_p\ \rho\ A\ V^3 \tag{3.4}$$

where, C_p is the aerodynamic efficiency, ρ is the air density in kg/m^3, A is the rotor covered area in m^2 and V is the wind speed in m/s.

The maximum theoretical limit of the aerodynamic efficiency is 0.59. While the commercial wind turbine efficiency varies from 0.35 to 0.45 depends on the turbine design [40].

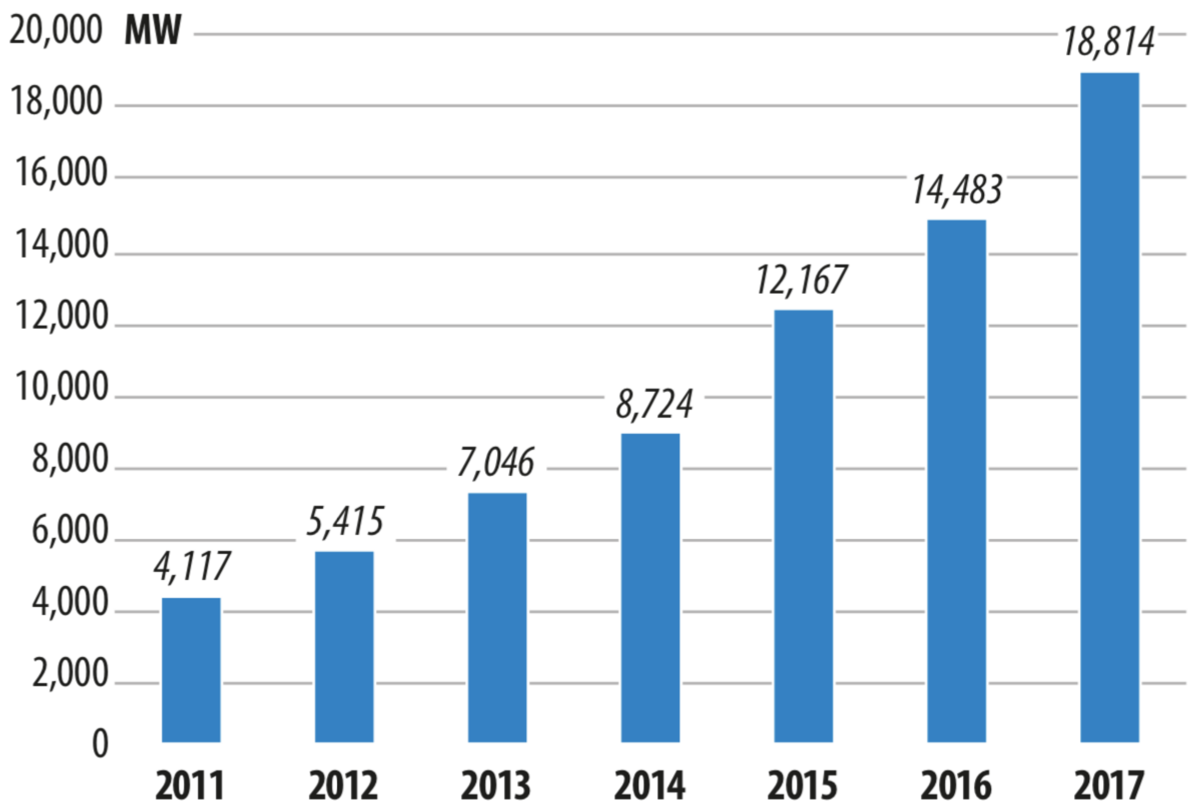

Figure 3.2: Offshore Wind Energy Installation Worldwide [52]

3.4. Discussion and Conclusion

After reviewing many technologies that can be used to supply the offshore platforms, it can be concluded that the available alternatives are as following: I) HVAC Transmission Lines, II) HVDC Transmission Lines, III) Gas Generator, and IV) Wind Turbines. Each of these technologies has its own pros and cons. The final decision of which technology to be used depends on the project requirements and vary from case to case. Moreover, some of those technologies are mature such as HVAC and gas generators. Other technologies are experiencing large advancements in the recent years. The VSC is more feasible for offshore application especially for large power capacity rated 350 MW and hence will be considered in this thesis [57].

CHAPTER IV

COST MODEL

The objective of this thesis is to solve the supply problem with two objectives the cost and reliability of the power source. In this chapter, a cost model is developed to estimate the present worth cost of the power supply from the power source to the common coupling point of the offshore load. In this chapter, the cost model of the algorithm will be discussed in details. First, the model methodology is illustrated. Each component is evaluated to develop a cost model as a function of the predefined parameter. Note that the cost will be in US Dollar with 2017 rates in all calculation.

4.1. Cost Model Methodology

The approach that has been used to obtain the cost model is first to collect available data from different publications. The data is analyzed to fit the purpose of the research. Finally, a number of equations are used to calculate the cost of each component. The overall cost is calculated by using Present Worth Analysis.

To make the model efficient the number of the required variable need to be reduced as much as possible without compromising the estimation accuracy. This will also help to make a fair comparison between different topologies with low available data. One of the challenges that need to be considered is time-dependent cost. Using historical data, which need to be adjusted to today cost. To encounter this challenge, the inflation rate has been considered in dealing with historical data and focusing on more recent data in the model. Note that this model's purpose is to evaluate different topologies and determine the optimal one.

4.2. System Components

All systems considered in this thesis will have a cost function that will be developed in this section. To have a systematic way of cost calculation for each system there will be common variables that will be used as an input depending on the system technical requirement and available data. The cost of the major components of the system will be calculated using those common variables only.

4.2.1. HVAC Transmission System

For the HVAC system, the major components, which are considered in the cost calculation, are shown in Table 4.1. The table also shows the required parameters to calculate the cost of each component. The number of used components will vary depending on the technical requirement. For example, a point to point AC direct connection will require having two switchgears and two transformers.

Table 4.1: HVAC Transmission System Component and Input Parameters

Component	**Input Parameters**
Transformer	Power in MW
Switchgear	Voltage in kV
Compensation	Voltage in kV and Power in MVar
Cables	Voltage in kV, Power in MW and Distance in km
Offshore Substation Platform	Power in MW

1) Transformer

The transformer data collected from [50]. A set of data obtained from European Network Transmission System Operator for Electricity (ENTSOE) and validated for high power up to 240 MW and 400kV. The model is shown in equation 4.1.

$$Cost_{Transformer} = 33384\ \mathrm{S}^{0.75920}\ \text{[USD]} \tag{4.1}$$

where S is the rated power in MVA.

2) Switchgear

The switchgear cost is voltage dependent. Even though the size depends on the rating current and available short circuit but the cost has proportional relation with the voltage level [59]. In [29], which was published in 2015, the cost model for AC switchgear is shown in equation 4.2.

$$Cost_{Switchgear} = 39564 + 741.76\,\mathrm{V} \quad [\mathrm{USD}] \tag{4.2}$$

where V is the nominal voltage in kV.

3) Compensation

The cost data is obtained from [29] and estimates the compensation cost to be 2/3 of the transformer cost since reactors have only one winding comparing to the transformers which have a minimum of two.

4) Submarine Cables

The cable cost data consists of two parts: the cable cost and the installation cost. The cable cost depends on the rated voltage which determines the insulation material and the cable capacity which determine the cross-section area. While the cost of the installation is basically the transportation and cable laydown cost. The cost used in [58] and referred to in [59] is modeled as an exponential equation with voltage-dependent parameters as shown in equation 4.3 and Table 4.2.

$$Cost_{AC\ Cable} = \mathrm{A} + \mathrm{B}\, e^{\frac{\mathrm{C\,S}}{10^2}} \quad [\mathrm{MUSD/km}] \tag{4.3}$$

where S is the rated power in MVA. A, B and C are constant shown in Table 4.4.

Table 4.2: AC Cable Cost Model Parameters

Nominal Voltage (Kv)	**A**	**B**	**C**
22	0.03124	0.06413	6.15
33	0.04521	0.06556	4.1
45	0.05676	0.06732	3
66	0.07568	0.06875	2.05
132	0.21681	0.02299	1.66
220	0.34991	0.01210	1.16

While the cable cost depends on the copper cost, the installation cost is highly dependents on the sea depth, distance from the transport and the seabed type. Since the purpose of this thesis is the comparison between different technology a fixed cost will be used with depth up to 30m and typical seabed [58]. The total cost of installation used in [58] is 316.16 kUSD/km. The installation cost of twin cables at the same trench is only 30% more than one cable installation. Moreover, the cost of installing two twin cables at two trenches is 70% more than one cable at one trench. It's assumed that the cost of three cables will be 50% more than one cable [59].

5) Offshore AC Substation Platform

The cost of the offshore platform depends on the desired services such as living spaces and auxiliary services. Moreover, the size of the electrical installation and location dependent parameters influence the cost of the platform. The platform cost model developed in [58] and [59] for substation is a function of the rated power as shown in equation 4.4.

$$Cost_{Substation} = 2635.36 + 92.248\,\mathrm{P} \quad [\mathrm{kUSD}] \tag{4.4}$$

where P is the rated power in MW.

4.2.2. HVDC Transmission System

The cost of HVDC system is similar to HVAC with different components. Table 4.3 shows the considered component in modeling HVDC and the input parameters.

Table 4.3: HVDC Components and Input Parameters for Cost Model

Component	Input Parameter
Transformer	Power in MW
Switchgear	Power in MW
Converter	Power in MW
Cable	Power in MW, Voltage in kVand Distance in km
Offshore Substation Platform	Power in MW

1) Transformer

The same transformer cost model of AC will be used. The equations 4.1 and 4.2. Where the only required input is the rated power.

2) Converter

The cost of the converter is the major difference in the overall cost of AC and DC transmission system. Even though the cost model depends highly on the used technology of the VSC, the cost model reported being voltage-dependent on many models. In [50] the cost model obtained from ENTSOE technical report [44] and it is modeled as shown in equation 4.5.

$$Cost_{VSC} = 0.0589\ \mathrm{P} + 57.18 \quad [\mathrm{MUSD}] \tag{4.5}$$

where P is power in MW.

3) Switchgear

The cost of DC substation is uncertain as reported in [29] due to different technologies used by different manufacturers for protection devices. An assumption has been made that the cost is four time higher than AC switchgear cost due to the complexity of the DC protection devices and others. The equation 4.2 multiplied by a factor of four will be used in the cost model.

4) Submarine Cables

Similar to the AC cable cost model, the DC cable cost consists of two parts; cable material and installation cost. However, it has been found that the DC cable cost is linearly dependent on the voltage and power. The model used in [58] is shown in equation 4.6 with different parameters for each voltage level shown in Table 4.4.

$$Cost_{DC\ Cable} = \mathrm{A} + \mathrm{B\,P} \quad [\mathrm{USD/km}] \tag{4.6}$$

Table 4.4: HVDC Cable Cost Model Parameters

Voltage [kV]	**A**	**B**
5	-38060	0.04488
40	-34540	0.006798
160	-11000	0.001804
230	8690	0.00132
300	31460	0.001066

The other part of the cable cost model is the installation cost. In [50] the cable cost stated to be unreliable due to significant difference reported from different sources. However, a cost of

416 kUSD/km is used. While in [29] the cost of DC cable installation is assumed to be 2/3 the cost of the AC system. This is justified by the size and weight are reduced in DC comparing to AC cables. The second cost will be used in this thesis.

5) Offshore DC Substation Platform

Generally, the cost of DC substation platform is higher than the AC platform due to additional components required in DC system. The authors in [50] assumed that the cost of DC substation is 85% higher than in AC system.

4.2.3. Wind Energy Systems

Wind farm cost consists of the unit cost, installation cost, maintenance and operation cost. The last cost model for wind systems reported by US EIA [51] in 2016. The report shows the cost of onshore wind systems and they stated that the cost of offshore wind systems is 25% higher. The final cost model is shown in equation 4.7. The OpEx of wind systems includes only a fixed cost and no variable cost. It is justified assumption since the wind systems are operated all the year. The OpEx expression is shown in equation 4.8.

$$Cost_{Wind\ Turbine} = 5{,}278{,}000\ \text{P}\quad [\text{USD}] \tag{4.7}$$

$$Cost_{Wind\ Turbine\ O\&M} = 397{,}000\ \text{P}\ [\text{USD}] \tag{4.8}$$

where P is Wind Turbine Power Capacity in MW.

4.2.4. Gas Generator

Due to the availability of natural gas on the offshore oil and gas platforms, many companies use gas genset to supply power, especially for a large installation. The cost model for gas generates is obtained from [51] published on 2016. The cost of typical Gas Generator consists of capital cost, fixed and variable cost of operation and maintenance as shown in Table 4.5.

Table 4.5: Gas Generation Cost Breakdown

Description	**Cost**
Capital Cost	678 USD/kW
Fixed Operation and Maintenance	6.8 USD/kW-Year
Variable Operation and Maintenance	10.7 USD/MWh

The capital cost includes the civil and structural installation of the generators. The operation and maintained cost include all require material and repair of the equipment. However, it doesn't include the fuel operation cost which depends on the fuel price and operation time. To calculate the fuel cost, the international price of natural gas is used from [62] on Jan 2018 to be equal to 151.5 USD per thousand cubic meters. While the hate rate of a typical gas generator is assumed to be equal to 10,340 kJ/kWh. Hence, the cost of energy from natural gas is 0.042 USD/kWh.

CHAPTER V

RELIABILITY ASSESSMENT MODEL

The other objective of the proposed algorithm is to find the most reliable solution. In this section, a composite reliability assessment model is presented. A Bayesian Network (BN) based model is proposed that combined the transmission line and distribution sources availability and adequacy.

5.1. Background

To illustrate the proposed reliability assessment model, some of the techniques used are explained. An overview of those techniques is presented in the section.

5.1.1. Reliability Assessment of Power System

To evaluate the reliability of power system we will use Loss of Load Probability (LOLP) at each load as an index which represents, the probability of a certain load will be down. To calculate the LOLP we need to identify the relationship between each component and the success and failure modes. A block diagram representation will be used to illustrate how to infer the state of power system component. Components are said to be in series if a failure of one component causes the whole system to be failed. On another hand, if a success of any component will cause the system to be in a success state that implies they will be connected in parallel. For example, if only one connection exists between two nodes and a failure of any component will interrupt that connection, then all the component of the connection will be represented in series. While if there exists a redundancy in a certain component of that connection and the failure of one of those components will not cause an interruption, then those components will be represented in parallel. The Availability of power system can be calculated as shown in equations 5.1 – 5.3.

$$Avaliability\ (A) = \frac{MTTF}{MTTF + MTTR} \tag{5.1}$$

$$MTTF = \frac{1}{\lambda} \tag{5.2}$$

$$MTTR = \frac{1}{\mu} \tag{5.3}$$

where MTTF and MTTR are mean time to fail and mean time to repair, respectively. While λ and μ are the failure and repair rate, respectively [34].

5.1.2. Bayesian Network

A Bayesian Network (BN) is a directed acyclic graph with its nodes refer to random variables and its arcs refer to direct influence between two nodes [63] – [65]. The random variable can be used to model a certain event with its probability. While each arc is used to indicate the cause and effect or direct relationship between two nodes. The arc starting node called parent node while the arc end node a child node. Moreover, a node without parent node is called root node. The relationship between the parent node and child is represented by a conditional probability distribution. The marginal probability distribution - the probability of events to occur -assigned to the root nodes, and it can be calculated for any child node using the conditional probability distribution. Both marginal and conditional probability distribution can be either continues or discrete. In case of discrete nodes, they can be represented in tables and called tabular form [63].

Figure 5.1 shows a Bayesian Network with four nodes with their marginal and conditional probability distribution. Each node represented by binary 0 or 1 events [65]. The root nodes are the only nodes that are defined by a marginal probability distribution (MDP), in the example in Figure 5.1 node C is the root node with 0.5 probability for both events. The child nodes are represented by conditional probability distribution given their parents. For example, the node S is defended with $P(S|C)$ in tabular form. The Joint Probability Distribution (JPD) can be used to defend the relationship between all events and the probability of a certain event to occur. A representation of the JPD using the chain rule of probability and the causality in a Bayesian Network shown in Figure 5.1 is shown in equations 5.4 – 5.5. Note that the Bayesian Network reduce the number of parameters from $2^4 - 1 = 15$ in case of chain rule to 9 parameters. The reduction is significant when dealing with large systems and provide huge advantage using Bayesian Network.

$$P(C,S,R,W) = P(W|C,S,R)\,P(R|C,S)\,P(S|C)\,P(C) \tag{5.4}$$

$$P(C,S,R,W) = P(W|S,R)\,P(R|C)\,P(S|C)\,P(C) \tag{5.5}$$

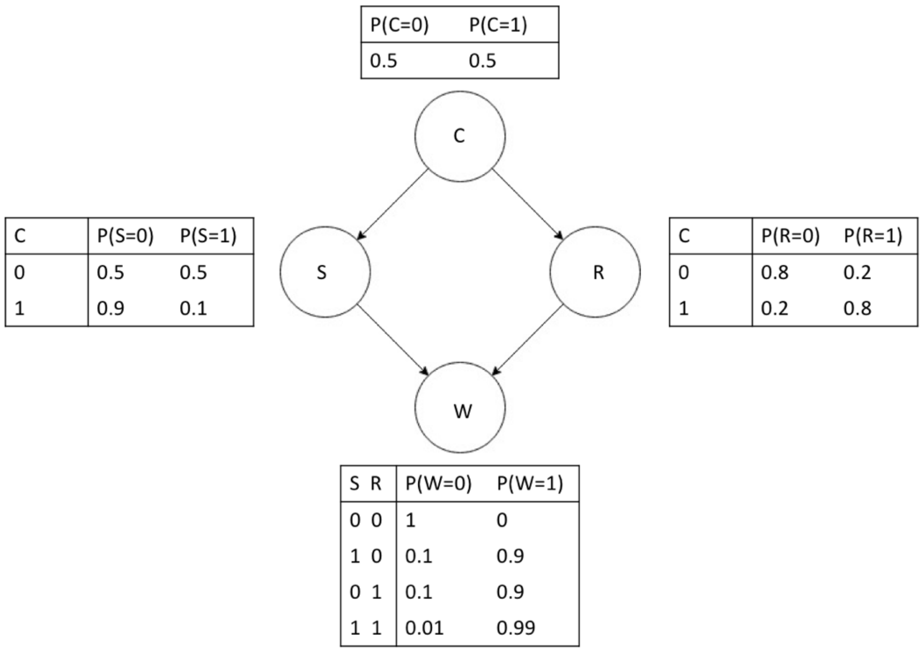

Figure 5.1: A Bayesian Network with MDP and CDP in Tabular Form

The behavior of the system can be modeled within the CDP. If a new knowledge that changes the behavior of the system is received, it could be easily incorporated. Moreover, the BN model can easily investigate the contribution of a certain event to other event and check the dependency or conduct cause-effect analysis [37].

5.1.3. Minimal Tie Sets

The Minimal Tie Sets (MTS) between two nodes is the minimum set of components needed to be in success state to provide continues connection between them [34]. To represent MTS between two nodes in the system, a series-parallel connection combination is used, where all components of one MTS are connected in series, and all MTS's are connected in parallel. The example shown in Figure 5.2 illustrates a complex system with its MTS's.

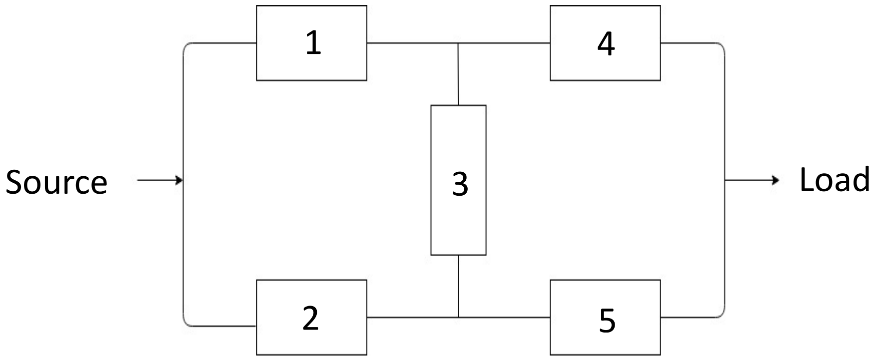

Figure 5.2: Block Diagram of Complex Series-Parallel System

To identify the MTS of a network, an enumeration with elimination is used. Where for a specific node to identify the MTS with another node we obtain all passable paths with length 1. Then the paths with length 2 are identified but all path with repeated nodes are eliminated. This process is continued until the target node appears. Figure 5.3 shows a flowchart of the method used to identify the MTS's of any network. For the system shown in Figure 5.2, the algorithm first will start by identifying two available walks routs from the sources sides, namely 1 and 2. Then, the next step the algorithm will identify six walks, three are from the first previous walk which is 1, and the other three from the other walk 2. So, the new W set will be {(S, 1, S), (S, 1, 3), (S, 1, 4), (S, 2, S), (S, 2, 3), (S, 2, 5)}. Since two of the walks contain repeated edges they will be removed from W at the elimination stage. The process will continue until no walks remained in Walks set then the algorithm is terminated. The final MTS's of the system in Figure 5.2 are {(S, 1, 4, L), (S, 1, 3, 5, L), (S, 2, 5, L), (S, 2, 3, 4)}.

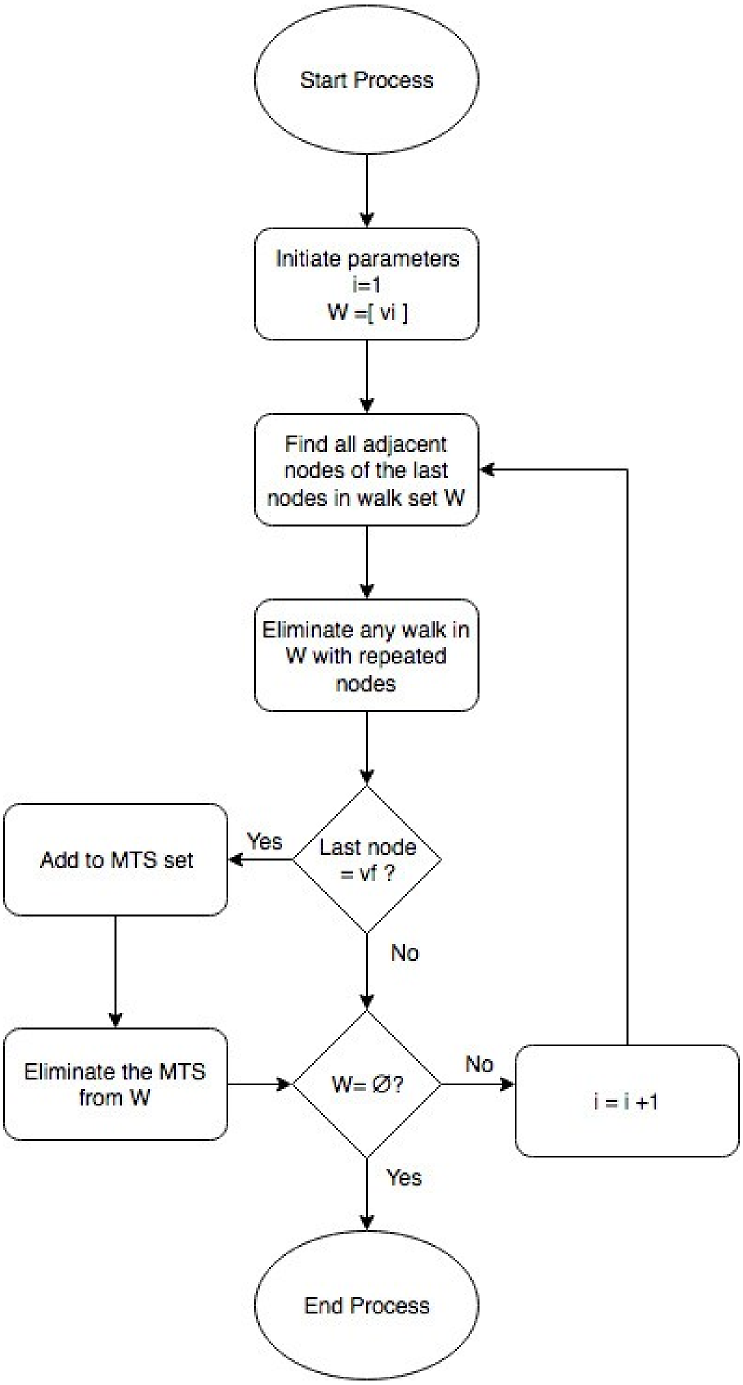

Figure 5.3: A Flowchart of the MTS Identification Algorithm

5.2. Reliability Assessment Methodology

In this section, the proposed model will be explained in details. The proposed BN model can be divided into three parts. The first part is concerned with the generation availability at each location. This part will include modeling the stochastic behavior of renewable generation and excess energy. The second part checks the connectivity of the network. That will give an insight into the connection availability between any two nodes. The third and last part is where the previous two parts are combined to calculate the LOLP. This part is the main contribution of this method where the available energy information received from the second part is integrated with the availability of the connection to transmit energy. Each part is explained in details in this section. To assess the reliability using the proposed technique the following assumptions are made:

- The failure of all components is assumed to be independent of each other and the failure of one component will not impact any other component.
- There is no constraint to the power connection capacity and it's assumed to be capable to transmit energy when it's available.
- The voltage constraints and the system stability are not considered in the evaluation. However, if it's deemed necessary, a power flow can be used at each success state and it will be changed to failure state if there is a violation.

5.2.1. Generation Availability Assessment

In this part, the generation side of the offshore power system is considered. Each load point will assumed to have generation sources represented by random variable. Since this model considers renewable sources, the generation state is time dependent. Two random variables are introduced to map represent the time in this method. Two random variables, one for the time of year and the other the time of day, are sufficient to capture the variability of the renewable sources accurately. Having unified time-dependent random variables will allow the model to capture the correlation of the different renewable sources type at different locations. e.g. if the wind speed at one location is high at certain season then it's more likely to be high at close locations.

5.2.2. Power Transmission Availability Assessment

The second part is used to account for power transmission availability. In this part, the components of all MTS's between nodes are identified. The MTS's availability is calculated using the identified transmission components. Where an AND operator is used between all component in one MTS, and an OR operator is used between all MTS's.

5.2.3. The Loss of Load Probability Calculation

The last step is to combine the generation and transmission sub-models to assess the reliability at each load point. The first model is used to ensure the adequacy of the generation while the second sub-model to ensure there is an available connection to transmit energy. To calculate the LOLP the Variable Elimination Algorithm is used to calculate LOLP. The system nodes type, parent, number of states and either they are deterministic or probabilistic are shown in Tables 5.1 – 5.3.

Table 5.1: The Nodes Parameters of The Generation Part

Random Variable	**Type**	**No. of State**	**Deterministic/ probabilistic**	**Parents**
Time of Year (ToY)	Root	|ToY|	Deterministic	N/A
Time or day (ToD)	Root	|ToD|	Deterministic	N/A
Wind Speed (WS)	Child	|ToY|*|ToD|	Probabilistic	ToY and ToD
Wind Generation (WG)	Child	Continues	Deterministic	WS
Gas Generation (GG)	Root*	Continues	Probabilistic	N/A
Local Generation Set (LGS)	Child	Continues **	Deterministic	WG, SG and DG
Grid Connection (GC)	Root	2	Probabilistic	N/A

* DG can be a child of fuel availability node if it is desired to be considered in the reliability assessment

**can be discretized for simplicity purposes

Table 5.2: The Nodes Parameters of The Transmission Part

Random Variable	**Type**	**No. of State**	**Deterministic/ probabilistic**	**Parents**
Transmission Line (TL)	Root	2	Probabilistic	N/A
Minimal Tie Set (MTS)	Child	2	Deterministic	TL

Table 5.3: The Node Parameters of the Composite Part

Random Variable	Type	No. of State	Deterministic/ probabilistic	Parents
Load Point (LP)	Child	|LP|	Probabilistic	ToD and ToY
Loss of Load (LOL)	Child	2	Deterministic	LP, MTS and LGS

5.2.4. Nodes State Representation

The nodes of BN model refer to random variables that can be divided into two categories: A) physical nodes, which refer to physical components such as power connection, and B) virtual one represents nonphysical components such as the minimal cut set. Each one of those nodes is connected to its child's nodes with Conditional Probability Distribution (CPD). The CPD can be either deterministic or probabilistic depending on the relationship between the parent node and child node.

A. Physical Nodes

A.1) Transmission Line

The Transmission Line node is a random variable with two states; either success or failure. It represents the state of the physical connection between two nodes. This includes the cables, switchgears, and transformers between those two nodes. It is assumed that those components are connected in series where a failure of any component will cause the connection to fail. A typical transmission line between two nodes consists of two switchgears at each end, two transformers at each end and a power cable. For simplicity, it will be assumed the connection consists of three components as shown in Figure 5.4. The Transmission Line availability can be calculated as shown in equations 5.6- 5.8.

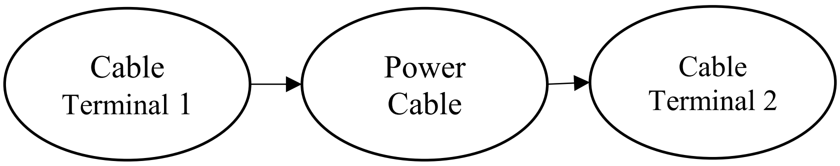

Figure 5.4: Power Connection Model Block Diagram

$$\lambda_{TL} = \lambda_{CT1} + \lambda_C + \lambda_{CT2} \tag{5.6}$$

$$r_{TL} = \frac{\lambda_{CT1} r_{CT1} + \lambda_C r_C + \lambda_{CT2} r_{CT2}}{\lambda_{CT1} + \lambda_C + \lambda_{CT2}} \tag{5.7}$$

$$P\left(TL_{ij} = 1\right) = Avalibility_{TL_{ij}} = 1 - \lambda_{TL}\, r_{TL} \tag{5.8}$$

where TL_{ij} is a random variable with two state represents the state of the Transmission Line between node i and j.

A.2) Wind Generator

The wind generator node is a random variable which represents the output power of the installed wind generation and its function of the time of day and year nodes and wind speed at the location of the wind generator. Using typical wind generator power output curve and historical wind speed data, the probability density function can be calculated as conditioned to the time and wind speed. Moreover, the availability of the generator is considered with two states up and down to determine the output states of a wind generator. The probabilistic graphical model for the wind generator node is shown in Figure 5.5.

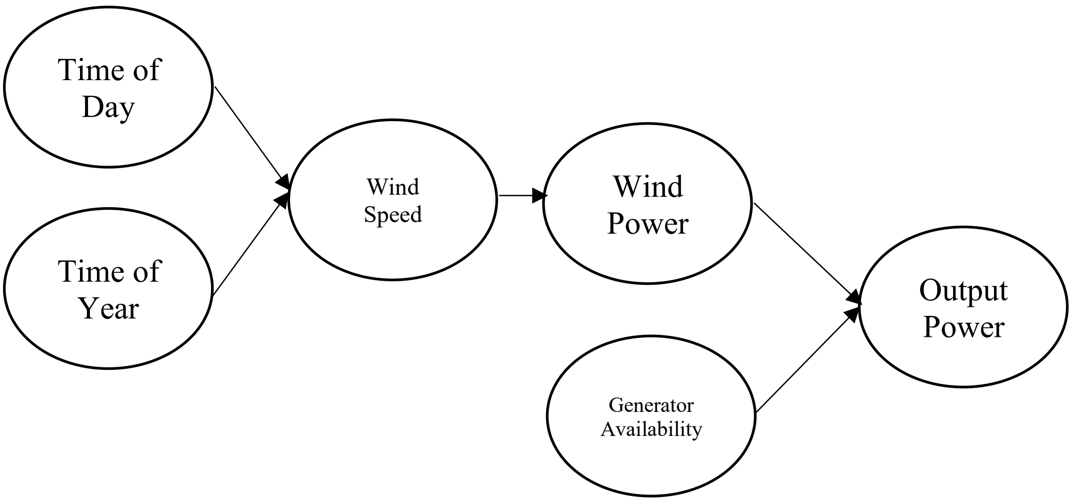

Figure 5.5: Graphical Model Representation of Wind System Power Output

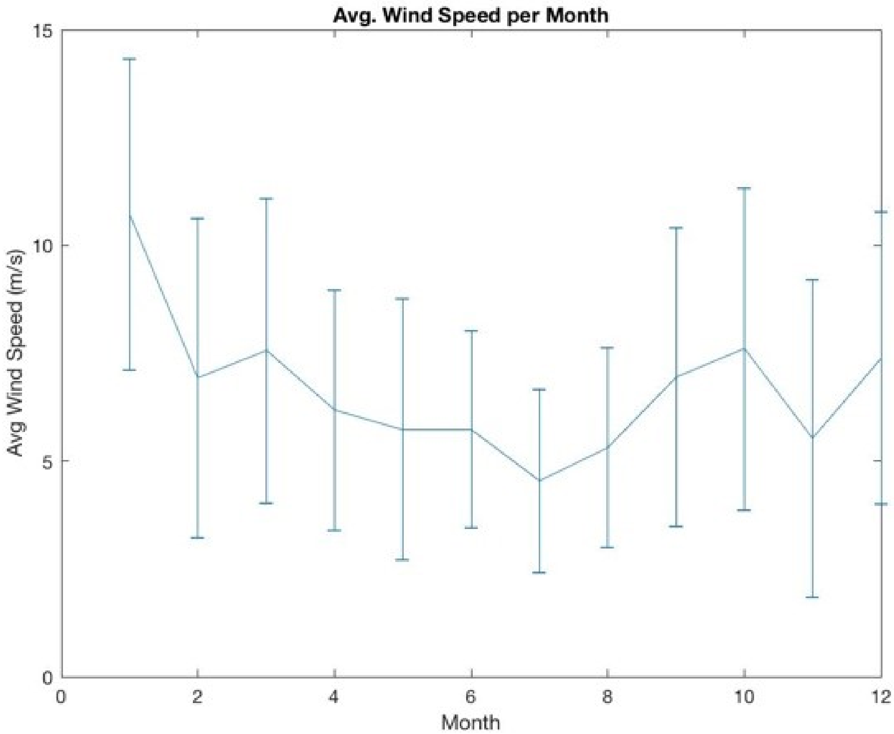

Figure 5.6: Monthly Average Wind Speed Data [67]

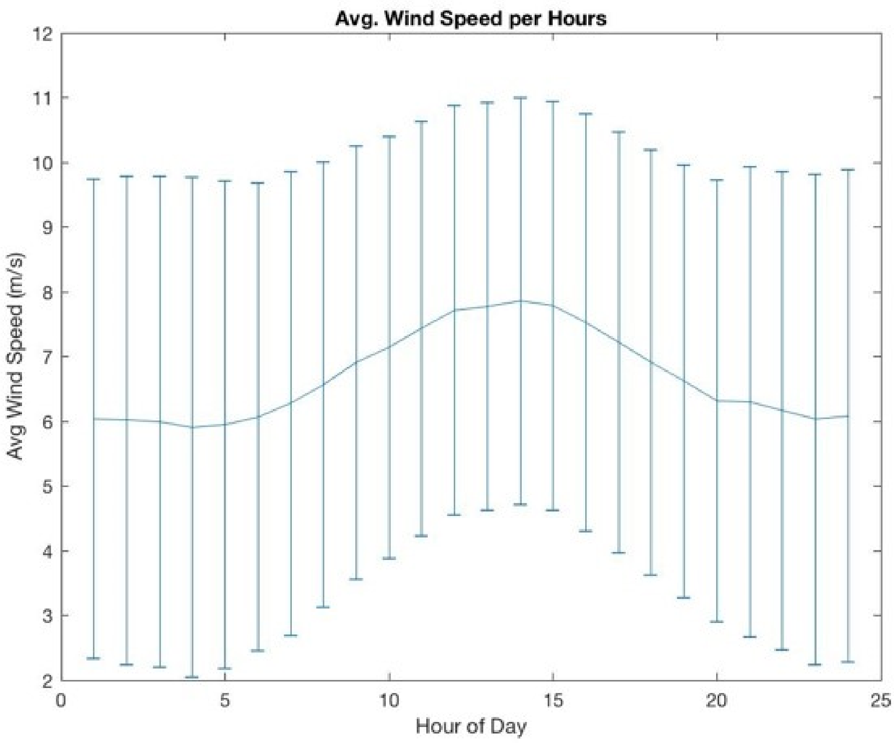

Figure 5.7: Hourly Average Wind Speed [67]

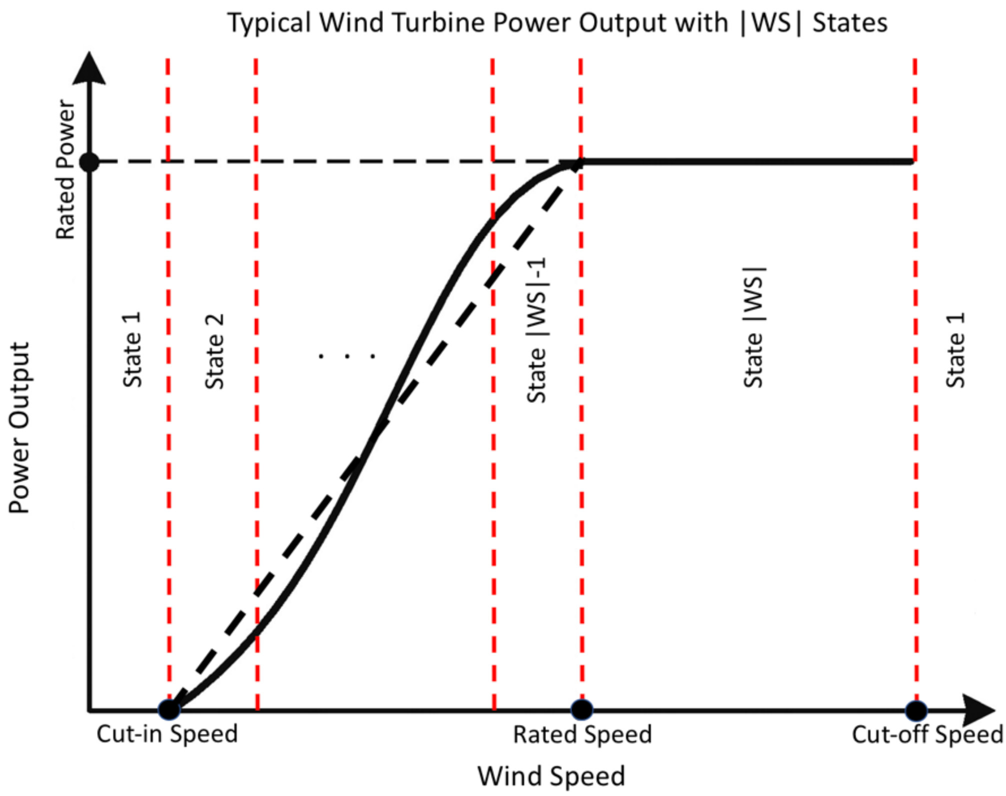

Figure 5.8: Typical Wind Speed Power Output Curve with The State Distribution

The Wind Speed states are calculated by using one-year wind speed historical data for each Time of Day and Time of Year. That can be represented with CDP as shown in equation 5.9. For simplicity purposes, the wind speed state will be discretized to |WS|+1 states. The first state is when the Wind Power is equal to zero, below the Cut-in Speed and above Cut-off Speed. The last state is when the wind speed between the Rated Speed and Cut-off Speed. Between those two sates, there are |WS|-1 states where the Wind Power is a function of the cube of Wind Speed.

The Wind Power is calculated for each state of wind speed variable using the typical wind generator power output curve as shown in Figures 5.6 - 5.8 [67]. The Wind Power will be discrete since the Wind Speed is discrete. For simplicity, it can be assumed a linear relationship between the Wind Speed and Wind Power at the transition region. The Generator Availability and the Wind Power are used as in the CDP of the Output Power of the wind turbine [32]. The wind speed, available wind power and wind system power output expression shown in equations 5.9 – 5.12.

$P(WS = ws) = P(WS = ws|ToD = d, ToM = m)\ P(ToD = d)\ P(ToY = m)$ (5.9)

$P(WP = wp) = P\ (WP = wp|WS = ws)\ P(Ws = ws)$ (5.10)

$P(GA\ =\ 0\ ) =\ FOR_{WG}$ (5.11)

$P(OP) = P(OP|WP, GA)\ P(WP)\ P(GA)$ (5.12)

Where WS, ToD, ToY, WP, and OP are random variables represent wind speed, time of day, time of year, Wind Power, and Output Power, respectively.

A.3) Gas Generator

This node refers to the state of the diesel generators at the desired location. Where a random variable with two states that represent up and down states of the generator. Moreover, the availability of the fuel could be considered to influence the state of the generators. The probability expression of the gas generation is shown in equations 5.13 – 5.14.

$P(GG_i = 0\ )\ =\ \ FOR_{GG}$ (5.13)

$P(GG_i = 1\ ) = 1 - P(GG_i = 0)$ (5.14)

where GG is a random variable represents gas generation state. $FOR_{GG}$is the force outage rate of the gas generator.

A.4) Grid Connection

This node represents the state of the grid connection at the common coupling point. A random variable is used with two states representing success and failure of the grid. If the grid fails that means the system will operate in islanding mode. If the grid is in success state, it's assumed that the power supply will always be sufficient to meet the demand. It's designed to supply the full demand regardless of the distributed generator status. The expression of the onshore power supply state is shown in equations 5.15 – 5.16.

$P(GC_i = 1\ ) = Avalibility_{GC_i}$ (5.15)

$P(GC_i = 0\ ) = 1 - P(GC_i = 1\ )$ (5.16)

where GC is a random variable represents onshore power supply state.

A.5) Load Point

The Load Point nodes refer to the load state of each platform. The Load state is a function of the time of the day and year. The Load profile can be calculated using the load profile data similar to Wind Speed. If the load profile is not available then it can be assumed the power demand is constant, and the Load is represented by a uniformly distributed random variable. The state expression of the load point is shown in equation 5.17.

$$P(LP = l) = P(LP = l|ToD = d, ToM = m)\ P(ToD = d)\ P(ToY = m) \tag{5.17}$$

Where LP is a random variable represents Load Point state.

B. Nonphysical Nodes

Nonphysical nodes or virtual nodes are introduced to capture the relationship between physical nodes and their interactions with each other. This will add the ability to capture the correlation between events occurrence.

B.1) Time of Day and Time of Year

Two nodes are used to represent the time of day and months. It's assumed that all renewable generation sources and the loads are functions of the time. Hence, those two nodes are used as parent nodes in the BN of renewable sources and load points. A deterministic uniformly distributed random variable is used to represent time nodes. The time is represented by two nodes because it's assumed that those two indicators are sufficient to capture the viability of the renewable recourses and the load change. The time of day and time of year states are shown in equation 5.18 – 5.19.

$$P(ToD = i) = \frac{1}{24}\ , for\ i = 1\ ,2\ , \dots, 24 \tag{5.18}$$

$$P(ToY = i) = \frac{1}{12}\ , for\ i = 1\ ,2\ , \dots, 12 \tag{5.19}$$

B.2) Minimum Tie Sets

The MTS's node represents the availability of the connection between two load point or load point and grid. It is a function of all transmission lines connecting those two points. It is a random variable with two states up and down. The availability of only one path between the two nodes will result in up states. While if one transmission line at each path of the MTS is down, this will result in down MTS.

As mentioned previously, the MTS is represented by series-parallel connection combination. Where all the components of one MTS are connected in series and all MTS's are connected in parallel. To model the MTS's between to nodes using BN, the MTS probability is shown in equations 5.20 – 5.22.

$$P(MTS_{ij}) = P(MTS_{ij}|TL_1, TL_2, \dots, TL_L) \prod_{k=1}^{L} P(TL_k) \quad (5.20)$$

$$P(MTS_{ij}|TL_1, TL_2, \dots, T:_L) = \begin{cases} 1 & if \ \cup_{k=1}^{M} MTS_{ij}^{k} = 1, MTS_{ij}^{k} \in MTS_{ij} \\ 0 & otherwise \end{cases} \quad (5.21)$$

$$MTS_{ij}^{k} = \begin{cases} 1 & if \ \cap_{r=1}^{R} TL_r = 1, TL_r \in MTS_{ij}^{k} \\ 0 & otherwise \end{cases} \quad (5.22)$$

Where MTS_{ij}^{m} is a random variable representing the state of MTS number m between node i and j, TL_d is a random variable for the state of the transmission line d, and k is number and k is number of transmission lines belong to the MTS between node I and j.

B.3) Local Generation Sets

The local generation node is the summation of the power output of all installed distributed generators. It's represented by a random variable that model the output power of installed DG's and can be calculated as the convolution of the power output of installed DGs. Equations 5.23 - 5.24 shows how to calculate the Local Generation Sets node.

$$P(LGS_i) = P(LGS_i|GG_i, WG_i,) \, P(GG_i) \, P(WG_i) \quad (5.23)$$

$$P(LGS_i = P|GG_i, WG_i) = \begin{cases} 1 & if \ \ GG_i * WG_i = P \\ 0 & otherwise \end{cases} \quad (5.24)$$

Where LGS_i is a random variable that represents the Local Generation Set state, each state is mapped to the total power output P. DG_i, WG_i, and SG_i are random variables that represent available Diesel Power Generation, and Wind Power Generation respectively, and the star notation represent convolution operation.

B.4) Loss of Load

The loss of load point node is the last child node in the BN. It's the representation of the load state either up or down based on its parent. The parents of each loss of load node are Local Generation Sets, Grid Connection, Minimum Tie Sets, and its load point.

The load availability can be calculated as follows; if the grid connection is in upstate and the MTSs connect the load to the grid is on that implies the load point is up. If the grid connection is in down state and the local generation state is more than the load state that imply the load is also in upstate. If the grid connection and local generation can't supply the load and the neighbor local generation can supply the demand and the all the MTS that connect those nodes are up then the load still up and can be supplied by those distributed generators of neighbor nodes. If none of the above cases applied then the load point will be in down state. This can be expressed by the expression shown in equations 5.25 and 5.26.

$$P(LOL_i) = P(LOL_i | LGS_1, \dots, LGS_M, GC_1, \dots, GC_G, MTS_{i1}, \dots, MTS_{i(M+G)}) \prod_{m=1}^{M} P(LGS_m) \prod_{g=1}^{G} P(GC_g) \prod_{j=1}^{M+G} P(MTS_{ij}) \quad (5.25)$$

$$P(LOL_i = 1 | LGS_1, \dots, LGS_M, GC_1, \dots, GC_G, MTS_{i1}, \dots, MTS_{i(M+G)}) = \begin{cases} 1 & if\ LGS_i \cup \sum_{j=1}^{G} GC_j\ MTS_{ij} \cup \sum_{\substack{j=1 \\ j\neq i}}^{M} LGS_j\ MTS_{ij} \geq LD_i \\ 0 & otherwise \end{cases} \quad (5.26)$$

Once the up and down states are known with their probability to occur, the Loss of Load Frequency (LOLF) can be calculated by summing the frequency of each component contribute to down state as shown in equation 5.27 [39].

$$LOLF = \sum_{i=1}^{n} [P(LOL_i = 1 | x_i = 1) - P(LOL_i = 1 | x_i = 0)]\ P(x_i = 1)\ \mu_i \quad (5.27)$$

Where x_i and μ_i is the state and repair rate of the i^{th} component, respectively. n is number of components. Knowing the LOLP and LOLF, the Loss of Load Duration (LOLD) can be calculated as shown in equation 5.28.

$$LOLD = \frac{LOLP\ 8760}{LOLF} \quad (5.28)$$

CHAPTER VI

COMMON BUS LOCATION

Installing a common bus to collect cables and lay down one cable is a common practice for large offshore installations. This will reduce the overall cost and increase the reliability of the network by allowing isolating faulted cables. A main advantage of the offshore substation is to allow having Multi-terminal HVDC network. In that case, three or more DC cables are connected at one station instead of point to point connection. The substation and converter cost of the HVDC system have a high penetration of the overall cost. Hence, connecting more than one DC cable to one substation will provide a cost-effective solution [69]. Also, that will add more flexibility to the system by allowing to have different network topologies and interconnect HVDC with HVAC whenever there is a cost benefit. In this chapter, a mechanism to find the optimum location of the offshore common bus is introduced. Where an optimization algorithm will be used to identify the optimum location based on the cable distance is proposed. A case study will be shown to estimate the saving cost of applying the proposed technique.

6.1. Common Bus Location Optimization Methodology

In order to find the optimum location for the common bus, an optimization problem is formulized. The objective of the optimization is to reduce the total length of all cables and it will be solved using Nelder Mead Method. The method is explained in details in [70]. The Euclidian distance as equation 6.1 shows will be used to represent the distance of each node in two Cartesian dimensions x and y. The common bus is denoted by i. The objective function is to minimize the summation of all Euclidian distance as shown in equation 6.2.

$$ED_{ij} = \left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2 \tag{6.1}$$

$$\min \sum_{\substack{\forall j \\ ij \in E}} ED_{ij} \tag{6.2}$$

where ED_{ij} is the Euclidian Distance between node i and j, E is the set of all edges in the network, x and y are the Cartesian locations of the nodes, i is the common bus index.

6.2. Case Study

To test the proposed method, a real case study is proposed. Four wind farms located offshore required to be connected to an onshore substation using transmission system. The proposed plan in [71] is to use direct point to point connection to the onshore substation. The Cartesian coordination of the offshore and onshore locations are shown in Table 6.1.

Table 6.1: Wind Farm Locations

	X	Y
Location 1	-30	65
Location 2	-22	70
Location 3	-17	65
Location 4	-5	68
Onshore	0	-30

By applying the proposed method, we obtain the optimum location of the common bus to be located near offshore substation 3. That implies the optimum topology is to connect all offshore substations to substation 3 and install one transmission line between substation 3 and the onshore substation as shown in Figure 6.1. The total cable distance, in this case, is equal to 129 km instead of 280 km for the direct connection to the onshore station. An enhancement of the proposed method can be achieved by using the cost of the transmission lines instead of Euclidian Distance. This simply can be applied using a modified version of equation 6.1 by multiplying the distance with weights that represent the cost of transmission line per km. An approximation is made that all the cables are HVAC with 122kV using the cost model to obtain the optimum location.

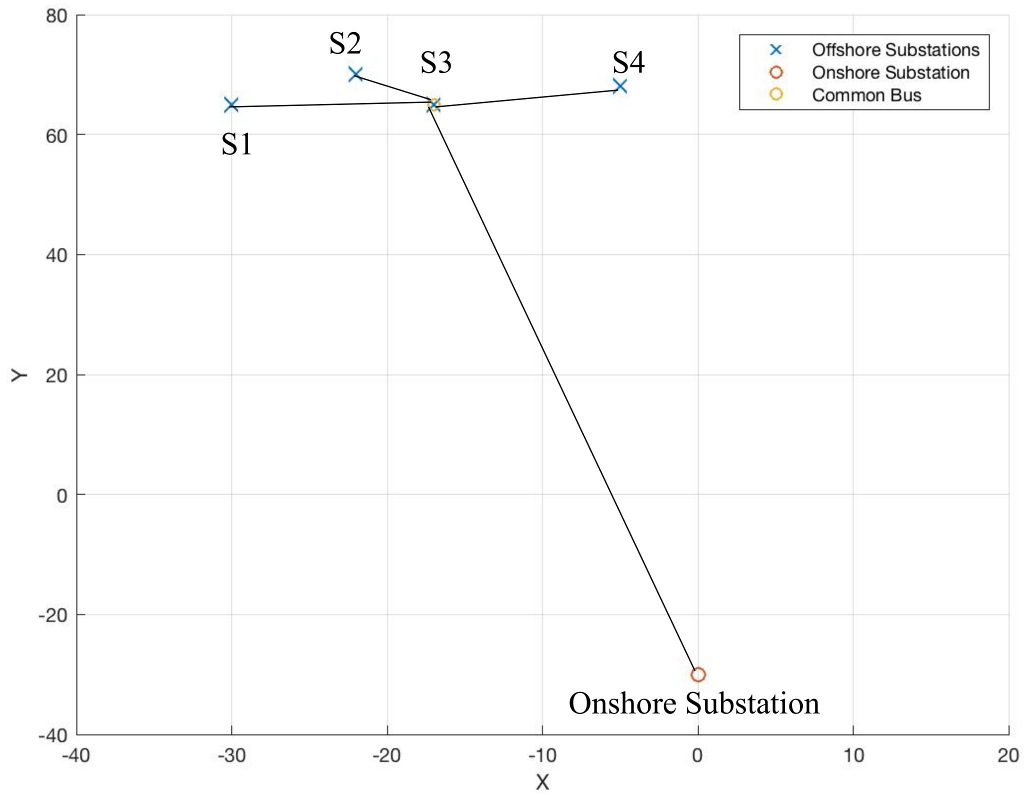

Figure 6.1: The Optimum Location for the Common Bus

CHAPTER VII

ELECTRIFICATION OF OFFSHORE GRID OPTIMIZATION

To search for the optimum solution, an optimization algorithm need to be used. There are several optimization techniques in the literature that proved its effectiveness. The methodology described in this thesis is categorized as a derivative-free optimization. The derivative of the objective function can't be calculated in this type of problems. Examples of those algorithms are; Genetic Algorithm, Simulating Annihilating and Practical Swarm Optimization [72]. A genetic algorithm-based optimization is used to find the optimum design. More details about genetic algorithm can be found in [73] – [76]. The solution of the problem is defined by the decision variables that identify a unique system. The output of the tool which is the decision variables is divided into two sets: the design parameters and optimization variables. The design parameters will be determined by the objective function. While the optimization variables will be coded as a chromosome and used as input for the objective function. More details about the decision variables and Design Parameters are shown in the next sections.

7.1. Optimization Variables

The optimization variables or the chromosome of genetic algorithm contains all the decision variables of the problem which will be used as input for the objective function which includes:

- Transmission Line Connection: TL_{ij}
- Wind Turbine Power Capacity at each Location: WP_i
- Gas Generators Power Capacity at each Location: GP_i

The chromosome lengths depend on the number of load points. For the transmission line topology, it will be coded using decision variable for each possible connection between any two nodes and "0" for the line doesn't exist, "1" for the line exist. Hence the number of Chromosome digits is equal to the number of edge of a complete graph as shown in equation 7.1.

The other two decision variables are related to the generation capacity of Gas and Wind generators. A discrete number will be used as decision variable to represent the generation capacity of each technology. Where the generation capacity is equal to the discrete decision variable multiplied by a constant. For example, if the constant is equal to 25, then if the decision variable is 4 for wind and 2 for gas that implies the generated capacity is equal to 100MW and 50MW for wind and gas generators, respectively. The number of discrete digits which will be added to the chromosome is equal to the number of load points as shown in equation 7.2. Each solution is defined with binary numbers represent the transmission line, discrete numbers represent the capacity of the distributed generators. The chromosome structure is shown in Figure 7.1.

$$Number\ of\ Binary\ Chromosome = \frac{N(N-1)}{2} \tag{7.1}$$

$$Number\ of\ Discrate\ Chromosome = S\ L \tag{7.2}$$

where N is the number of nodes that includes load node, common bus, and onshore node. L is number of load points and S is number of available Distribution Generation technologies.

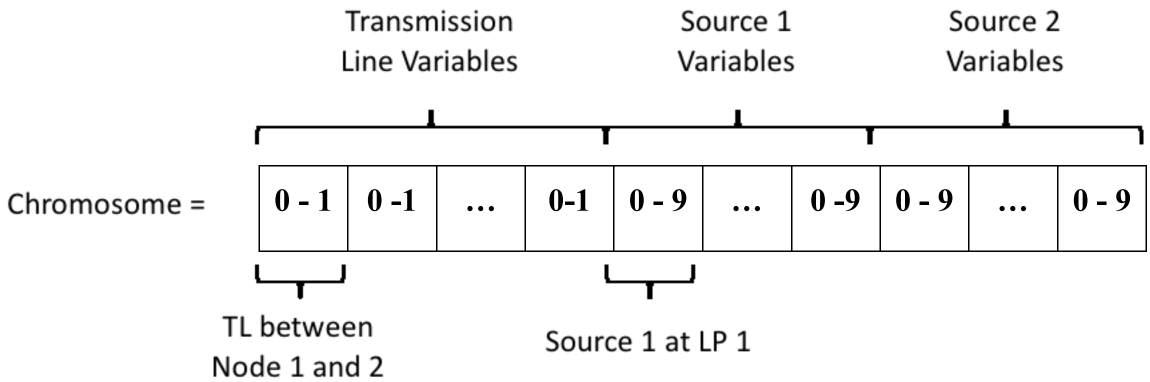

Figure 7.1: The Optimization Variable Coding

7.2. Design Variables

There are many variables that found and optimized once the optimization variables are determined. Those variables are the design variables and will be used to evaluate the objective function along with the optimization variables. Some of those design variables can be calculated directly using predefined equations such as cable capacity, power consumption from the distributed generators and the onshore grid. Other design variables can be identified using optimization algorithms such as the transmission line voltage and common bus location. More details about the design variables are shown in the overall workflow of the algorithm section.

7.3. Objective Function

The objective function formalized to minimize the overall cost of the project and increase the reliability of the system. A multi-objective function with two objectives is used:

- Minimize overall system cost in USD
- Increase system reliability which will be represented by minimizing Loss of Load Probability (LOLP)

To solve the multi-objective function and find the Pareto Front, a single objective function will be used that merge the two objectives using weights for both objectives. The weights actually have meaningful representation which is the Cost of Non-Served Energy (CNSE) and will be multiplied by LOLP as shown in equation 7.3.

$$Objective\ Function\text{: } \min\ (CostSystem + LOLP * 8760 * CNSE * PWF) \qquad (7.3)$$

where $CostSystem$ is the present worth value of the system, $LOLP$ is the loss of load probability, $CNSE$ is the Cost of Non-Served Energy, and PWF is the present worth factor The objective function is nonlinear when considering the cost of the system and how to calculate the LOLP.

7.4. Constraints

The objective function is subjected to many constraints. Some of them related to the optimization variables, other have to do with the design variables which will be considered during the design variables determination step. The constraints on the optimization variables are: the total power of any distributed generation shall not exceed the installed load capacity and the common bus shall have at least two connections to the load. The first constraint is introduced to ensure the solutions satisfy the minimum reliability requirement and eliminate any unreliable solution. The second constraint is used to have a ceiling to the maximum power of distributed generation, especially for renewable resources. While the last constraint to ensure the common bus is used for the purpose of having multi-terminal transmission line and not as redundant connection only. The three constraints are shown in equations 7.4 – 7.6.

$$Subjected\ To: \qquad LOLP \geq LOLP_{min} \tag{7.4}$$

$$DG_i^t \leq LP_i \tag{7.5}$$

$$TL_{1c} + \cdots + TL_{nc} > 1 \tag{7.6}$$

where $LOLP_{max}$ is the maximum allowable reliability for the power system.

DG_i^t is the power capacity of distributed generator at load location i with technology t (wind or gas generators in this case).

LP_i is the installed load capacity at location i.

TL_{1c} is the transmission line indicators that represent the connection between load location 1 to the common bus c.

The number of constraints equations depends on the number of load points and the number of available distributed generation technology. If there are existing components installed and the objective is to upgrade or modify the existing system, additional constraints can be added to the optimization to reflect those components. The cost of the component will offset the cost of all search space in that case and will not affect the optimization. However, when we want to calculate the cost of the modification we simply subtract the existing component cost from the optimum solutions. Moreover, a special case is considered where the offshore load is supplied by existing generators. In that case, only the OpEx will be considered in the optimization and there will be no capital cost.

7.5. Algorithm Workflow

The optimization problem is solved in a modular base. Several modules are used, where each module has a specific objective, inputs, and outputs, interconnected with each other in certain order. The overall workflow is shown in Figure 7.2. Each module objective, inputs, and outputs are illustrated in this section starting from the Start Module to the End Module. In Figure 7.2, the red modules are related to the genetic algorithm and its operators including the optimization variables. The green modules are related to the objective function evaluation including the design variables determination. While the blue modules are the user interface where the user will specify the optimization inputs and display the optimization outputs. Moreover, two modules are highlighted with bold borders namely, the Common Bus Location Optimization and the Transmission Line Design Optimization, to indicate that their process includes an optimization which will be explained later at their sub-section.

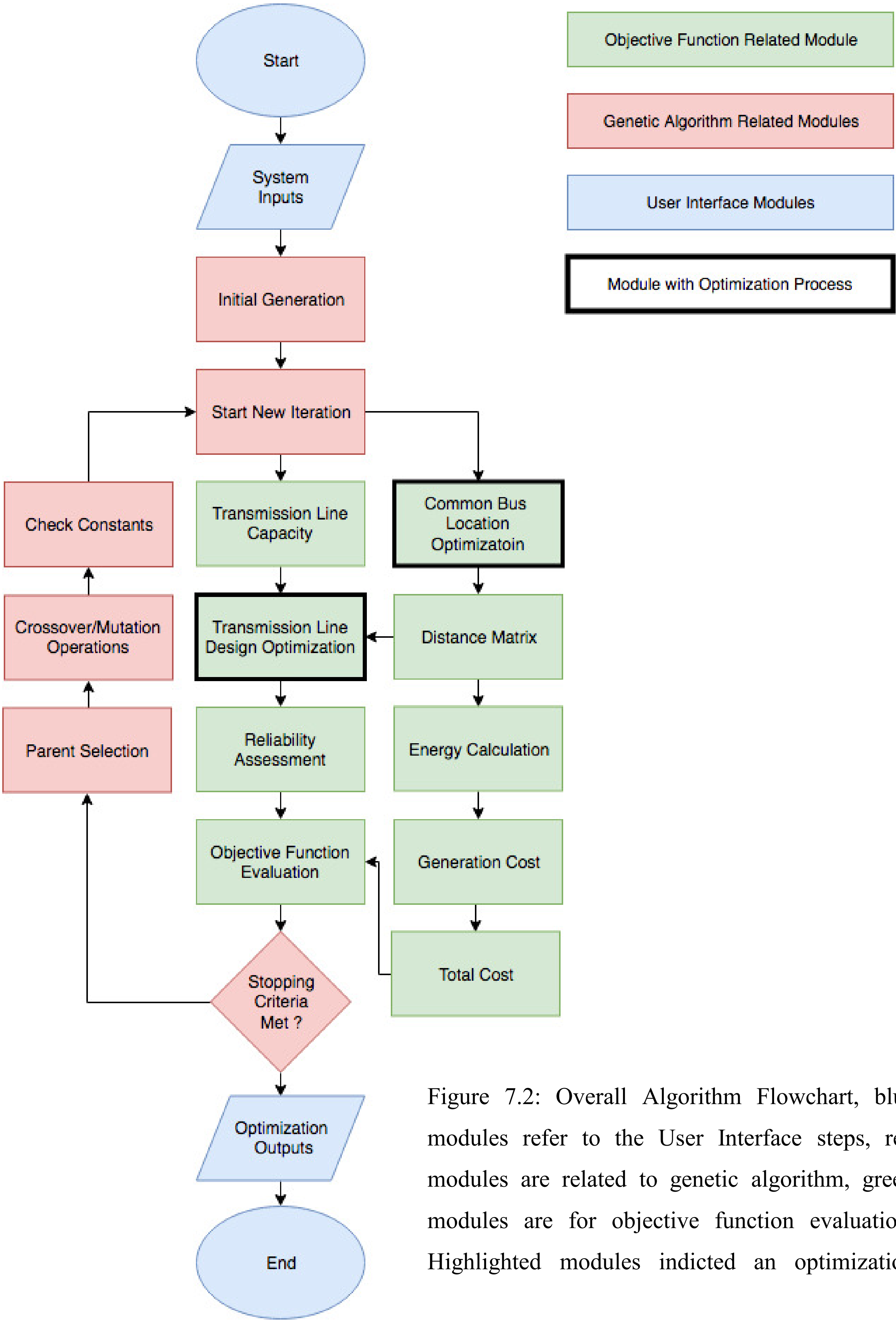

Figure 7.2: Overall Algorithm Flowchart, blue modules refer to the User Interface steps, red modules are related to genetic algorithm, green modules are for objective function evaluation. Highlighted modules indicted an optimization

Module 1: Tool Inputs

The developed tool is meant to be used by the decision makers with the lowest number of inputs parameters. This module is a user interface and the user can insert the algorithm inputs. The required inputs for the tool are the following:

- Cartesian coordination of Loads and Onshore Substation $Location\ X_i, Location\ Y_i$
- Installed Load at each location: LP_i
- Hourly Wind Data at Load Location: WS_i
- Cost of Non-Served Energy: $CNSE$

Module 2: Initial Optimization Variable (Initial Generation):

In this stage, random solutions are generated equal to the number of genetic algorithm population and subjected to the problem constraints. The initiated variables are:

- Transmission Line Connection: TL_{ij}
- Wind Turbine Power Capacity at each Location: WP_i
- Gas Generators Power Capacity at each Location: GP_i

Module 3: Start New Iteration

This module initiates the current generation of the genetic algorithm. In this module, the new generation is received. Each solution is defined by optimization variables. Moreover, the current population includes the elitism population from the past generation.

Module 4: Transmission Line Capacity

Once the load capacity and transmission line connection are identified, the capacity of each transmission line can be calculated. It is important to optimize the design capacity for the power rating of each cable link. To find the optimum design a power flow for all possible scenarios is conducted and select the maximum power flow over each transmission line as the cable capacity. The inputs to this module are:

- Installed Load at each location: LP_i
- Transmission Line Connection: TL_{ij}

The output of this module is one of the design variables which is:

- Transmission Line Capacity: TLC_{ij}

Module 5: Common Bus Optimum Location

This module includes an optimization algorithm to find the optimum location of the common bus. This module objective is to find the optimum location of the common bus using the system connections and locations that reduce the system cost. The Inputs of this modules are:

- Cartesian coordination of Loads and Onshore Substation $Location\ X_i, Location\ Y_i$
- Transmission Line Connection: TL_{ij}
- While the output is:
- Common Bus Location: $Location\ X_c, Location\ Y_c$

The output as mentioned earlier:

- Cartesian coordination of Common Bus: $Location\ X_c, Location\ Y_c$

Module 6: Distance Matrix

This module calculates the Euclidian Distance between any two nodes including the load, common bus and onshore substation locations. The Euclidian Distance is defined as shown in equation 7.7.

$$ED_{ij} = \left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2 \qquad (7.7)$$

Where the d_{ij}, the entry of matrix D, is equal to ED_{ij} which represent the distance between node i and j in km.

The inputs of this modules are:

- Cartesian coordination of Loads, Common Bus and Onshore Substation $Location\ X_i, Location\ Y_i$

While the output of the module is:

- Distance Matrix: D

Module 7: Transmission Line Design

This module is another optimization to find the optimum design of the transmission line that reduces the transmission line cost. The designs parameters are limited to certain standards and it is fixed. The optimization is solved by enumerating all possible scenarios that satisfy the problem constraints and find the lowest cost among them. This module will be used for each transmission line connection to find the optimum design. The flowchart of this module is shown in Figure 7.3. The Input of this module are:

- Transmission Line Connection: TL_{ij}
- Transmission Line Capacity: TLC_{ij}

- Distance Matrix: D

Calculating the transmission line cost will be done during this module to eliminate redundancy and optimize the algorithm. The cost will be used as an output of this module in the total system cost step. The outputs of this module are:

- Transmission Line Technology: TL_{ij}^{Tech}
- Number of Cables: TL_{ij}^{n}
- Transmission Line Voltage: TL_{ij}^{V}
- Transmission Line Cost: $TLCost$

Module 8: Reliability Assessment

The reliability assessment module is a main module in the algorithm. In this module, the reliability is calculated. Moreover, the probability distribution of the generation source operation is calculated, which will be used for energy calculation. The inputs of the module are:

- Transmission Line Connection: TL_{ij}
- Transmission Line Technology: TL_{ij}^{Tech}
- Transmission Line Capacity: TLC_{ij}
- Distance Matrix: D
- Installed Load at each location: LP_i
- Hourly Wind Data at Load Location: WS_i
- Wind Turbine Power Capacity at each Location: WP_i
- Gas Generators Power Capacity at each Location: GP_i

Other fixed parameters are included within the reliability assessment module such as the transmission line failure rate, repair time for each transmission technology, the Force Outage Rate (FOR) of the gas generator units, wind systems, and the grid availability. The outputs of the module are:

- Loss of Load Probability: $LOLP$
- Wind Generation States Probability Distribution: WG_i
- Gas Generating States Probability Distribution: GG_i
- Grid Connection States Probability Distribution: GC_i

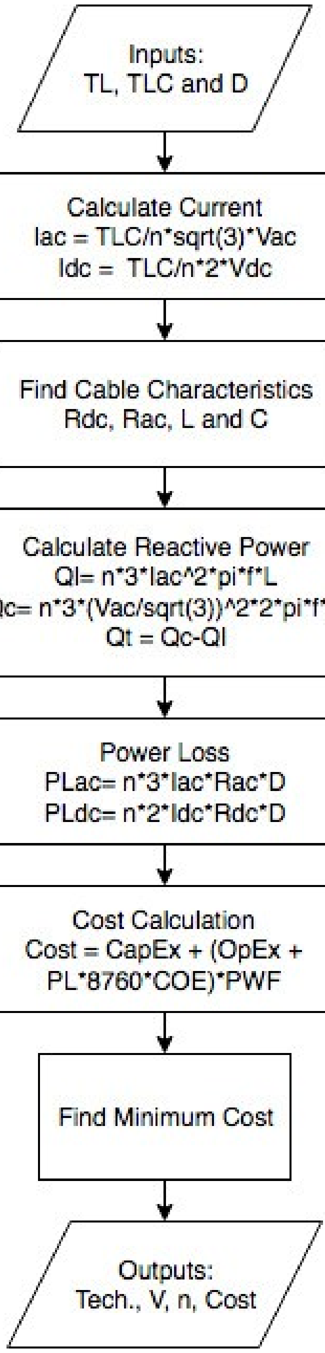

Figure 7.3: Transmission Line Design Optimization Steps

Module 9: Energy Calculation

In this module, the yearly energy profile is estimated using inputs from reliability assessment. To estimate the energy profile, the number of the isolated networks are identified. Each network is checked if they are connected to the grid or not. The grid-connected topology will be treated differently from off-grid.

1) For the grid connected, it's assumed that the renewable energy is the main source and the excess energy will be sold to the grid. If there is a shortage of the generated energy from renewable sources, the system will use the grid to compensate that shortage. Moreover, the gas generators will generate energy only in the cases when there is no renewable nor the grid energy is available. The energy selling and purchasing from the grid can have different prices depends on the existing regulation. The selling and purchasing price are the same and net metering policy is applied. 2) For grid isolated case, the renewable sources also will be the main source of energy, however, the gas generators will work in parallel to compensate for the shortages. The overall flowchart of this module is shown in Figure 7.4. The Inputs of this module are:

- Transmission Line Connection: TL_{ij}
- Installed Load at each location: LP_i
- Wind Generation States Probability Distribution: WG_i
- Gas Generating States Probability Distribution: GG_i

The outputs are:

- Yearly Energy Consumption: EC
- Yearly Energy Generated by Gas Generators: GGE
- Yearly Energy Generated by Wind Turbines: WE
- Yearly Energy Purchased from the Onshore Grid: GE

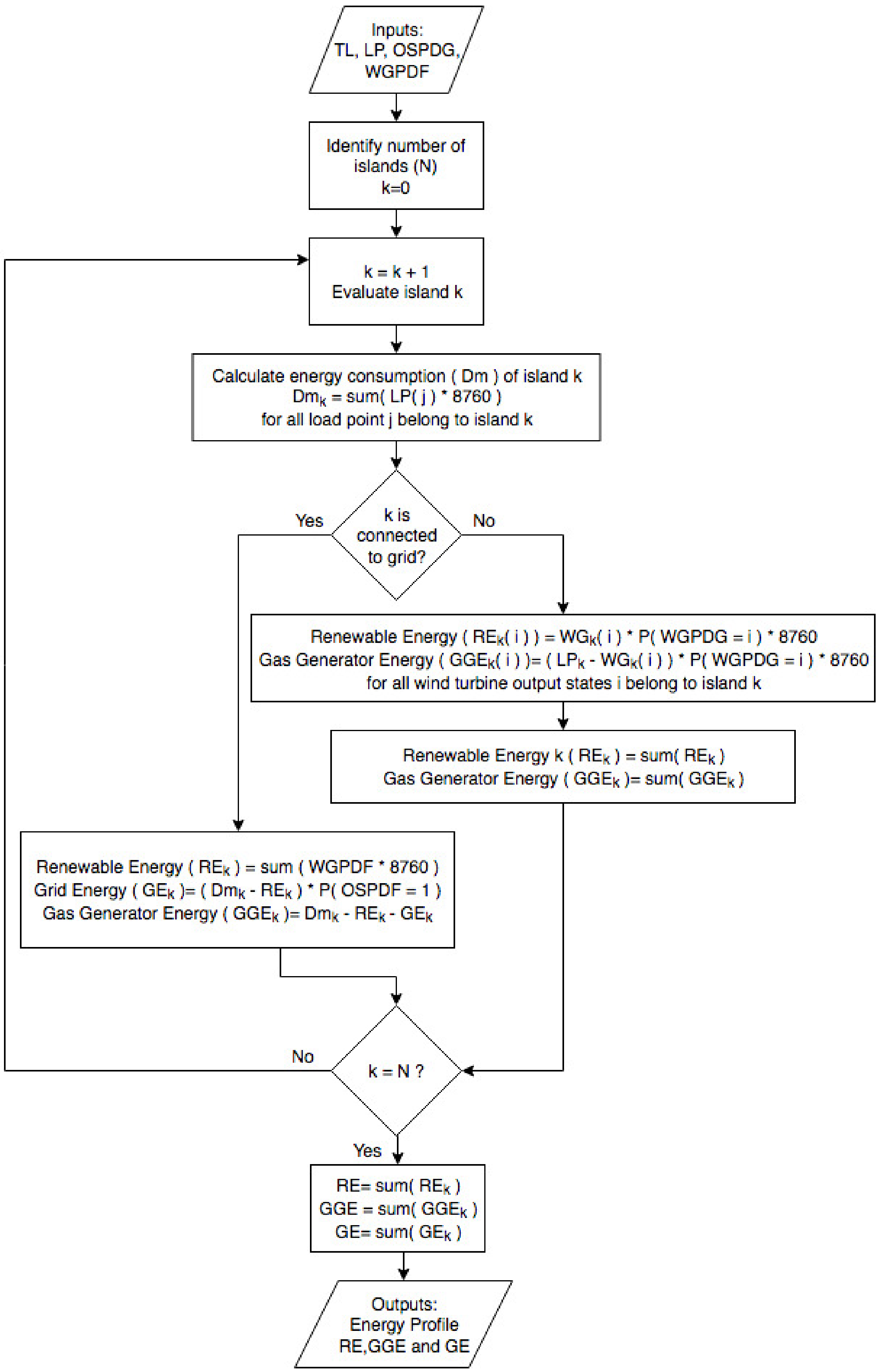

Figure 7.4: Energy Calculation Flowchart

Module 10: Generation Cost

The calculation of the total generators cost including wind and gas generators is done in this module. The cost can be calculated as shown in equations 7.8 – 7.10.

$$CostGen = CostGG + \ CostWT \tag{7.8}$$

$$CostGG = CapExGG + (FixOpExGG + VarOpExGG \ \ GGE)\ PWF \tag{7.9}$$

$$CostWT \ = CapExWT + (FixOpExWT + VarOpExWT\ WE)\ PWF \tag{7.10}$$

Where PWF is the present worth facor. The Inputs of this module as following:

- Wind Turbine Power Capacity: WP
- Gas Generators Power Capacity: GP
- Yearly Energy Generated by Gas Generators: GGE
- Yearly Energy Generated by Wind Turbines: WE

The output of this module is:

- Total Generation Cost: $CostGen$

Module 11: Total Cost

The cost calculation module is the second main module to evaluate the objective function. In this module, data from the transmission line and the generator costs modules are received in addition to energy consumption from each source. Equation 7.11 is used to calculate the total cost of the system.

$$CostSystem = CostGen + TLCost + (GE\ COE + GGE\ COGE)\ PWF \tag{7.11}$$

Where PWF is the present worth factor. That makes the Inputs of this module as following:

- Total Generation Cost: $GenCost$
- Transmission Line Cost: $TLCost$
- Yearly Energy Generated by Gas Generators: GGE
- Yearly Energy Purchased from the Onshore Grid: GE

While the output of the module is:

- Total System Cost: $CostSystem$

Module 12: Objective Function Evaluation

This module basically calculates the objective function. The input variables are:

- Total System Cost: $CostSystem$
- Loss of Load Probability: $LOLP$

While the output is:

Objective Function Value: $ObjFunVal$

Module 13: Parent Selection

After evaluating the objective function for all population, the parents of the new generation will be selected in this module. Out of the current population, we will randomly select two samples to be the new parent with higher probability to select the fittest. Then another parent is selected to generate two new samples using the crossover and mutation operators. This operation will be repeated until we have new samples equal to the number of population. The Inputs of this module are:

Objective Function Value: $ObjFunVal$

The output of this module is the parents Indices

Module 14: Crossover/ Mutation Operators

To generate new population, crossover and mutation operations are conducted to the selected parents. For the crossover, a binary BLX-α crossover is used. A non-uniform mutation is used for mutation [76].

The inputs of the module are the parent optimization variables:

- Parent Transmission Line Connection: TL_{ij}
- Parent Wind Turbine Power Capacity at each Location: WP_i
- Parent Gas Generators Power Capacity at each Location: GP_i

The outputs are the new generation optimization variables:

- New Generation Transmission Line Connection: TL_{ij}
- New Generation Wind Turbine Power Capacity at each Location: WP_i
- New Generation Gas Generators Power Capacity at each Location: GP_i

Module 15: Check Constraints

This module will check the new generation and set their value to be within the search space. The inputs of this module are the new generation after the mutation operation is completed. While the outputs are the new generation after ensuring they don’t violate any constraints.

Module 16: Stopping Criteria

In this module, the optimum value is checked to see if there is an improvement from the last generation. The Stopping Criteria Module will terminate the optimization if there is no improvement in a certain number of generation (Stopping Criteria Parameter) or if the number of generation exceeds predefined value (Maximum Number of Generation). Otherwise, the optimization continues and the process is repeated until it is terminated.

Module 17: Optimization Outputs

If the Stopping Criteria is satisfied the output of the algorithm is displayed in this module. The outputs of the algorithm are:

- Optimum Transmission Line Connection: TL_{ij}
- Optimum Wind Turbine Power Capacity at each Location: WP_i
- Optimum Gas Generators Power Capacity at each Location: GP_i
- Yearly Energy Generated by Gas Generators: GGE
- Yearly Energy Generated by Wind Turbines: WE
- Yearly Energy Purchased from the Onshore Grid: GE
- Total System Cost: $CostSystem$
- Loss of Load Probability: $LOLP$
- Transmission Line Technology: TL_{ij}^{Tech}
- Number of Cables: TL_{ij}^{n}
- Transmission Line Voltage: TL_{ij}^{V}
- Transmission Line Capacity: TLC_{ij}

CHAPTER VIII

IMPLEMENTATION AND RESULTS

In this chapter, the proposed algorithm will be implemented to check the optimum plan to supply offshore facilities. Several case studies will be shown to explain the offshore platform electrification problem and show the solution at different scenarios. Moreover, the features and capabilities of the proposed methodology will be discussed and presented.

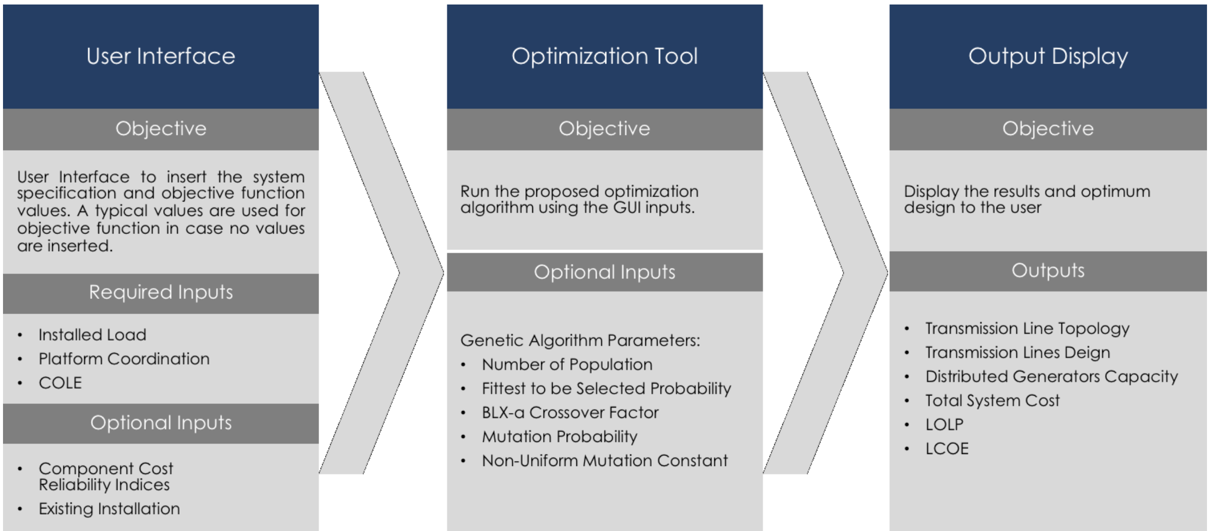

Figure 8.1: Proposed Architecture for UI Tool

The developed algorithm is designed to be Decision Support System (DSS) to help the decision makers and engineers to make an informative decision. The proposed algorithm is using state-of-art algorithms that aim to find the optimum design in term of the used technology, component design, and the feasibility of the system. The proposed algorithm can be wrapped into a User Interface (UI) to allow the decision maker to insert the specification of its own problem. Moreover, an optional parameter, including the cost of the system and genetic algorithm parameters, can be modified. This will add flexibility to the algorithm to account for any new update or newly available data, which can be modified by the user. However, if the user doesn't want to add any values more than the system specification, typical values from literature have been adapted. In this way, the proposed UI will facilitate the user experience by requiring minimal number of parameters and keep the possibility to modify more parameters. The architecture of the proposed UI tool is shown in Figure 8.1.

To use the algorithm, the Cost of Non-Served Energy (CNSE) need to be selected. Different values can be used to estimate the CNSE. An option could be to use the international oil price to gauge the value of losing the production of each barrel. Another option is to use the shadow price of the oil, which is independent of the international price and not publicly available. The proposed model is designed to consider the variations of the CNSE. The typical oil and gas production of GOSP varies from 150,000 to 450,000 barrels per day and about 140 Million standard square Feet per day, equivalent to 164,780 cubic meters per hour [77]. Using the international price of oil on April 27, 2018, which is equal to 71 USD/Barrel, and the US Gas price from USEIA website, equal to 151.5 USD per thousand meters cube. The CNSE for one hour of a mid-size GOSP is estimated to be 887,500 USD/Hour of Interruption of one Gas Oil Separation Plant (GOSP). Using the shadow price obtained from oil and gas company the CNSE is estimated to be 240,000 USD/Hour of Interrupting.

8.1. Case Study 1: Electrification of Single platform

To evaluate the algorithm, the cost of electrification of single offshore platforms will be verified. The solution of this case will be a general guideline for the electrification problem with the simplest case. Moreover, this will allow to evaluate and verify the proposed algorithm and compare different solution in the simplest form. The lifetime of the project is considered to be 20 years and the discount rate is 5%.

8.1.1. Problem Description

The objective here is to supply single offshore platform using the developed tool. In this case, the platform is defined by the distance from the onshore substation, and the power consumption of the platform. For illustration purposes, Figure 8.2 shows a single offshore oil field required to be supplied. The objective is to supply the offshore platform with varying distance and installed power. The evaluation will be based on the overall system cost.

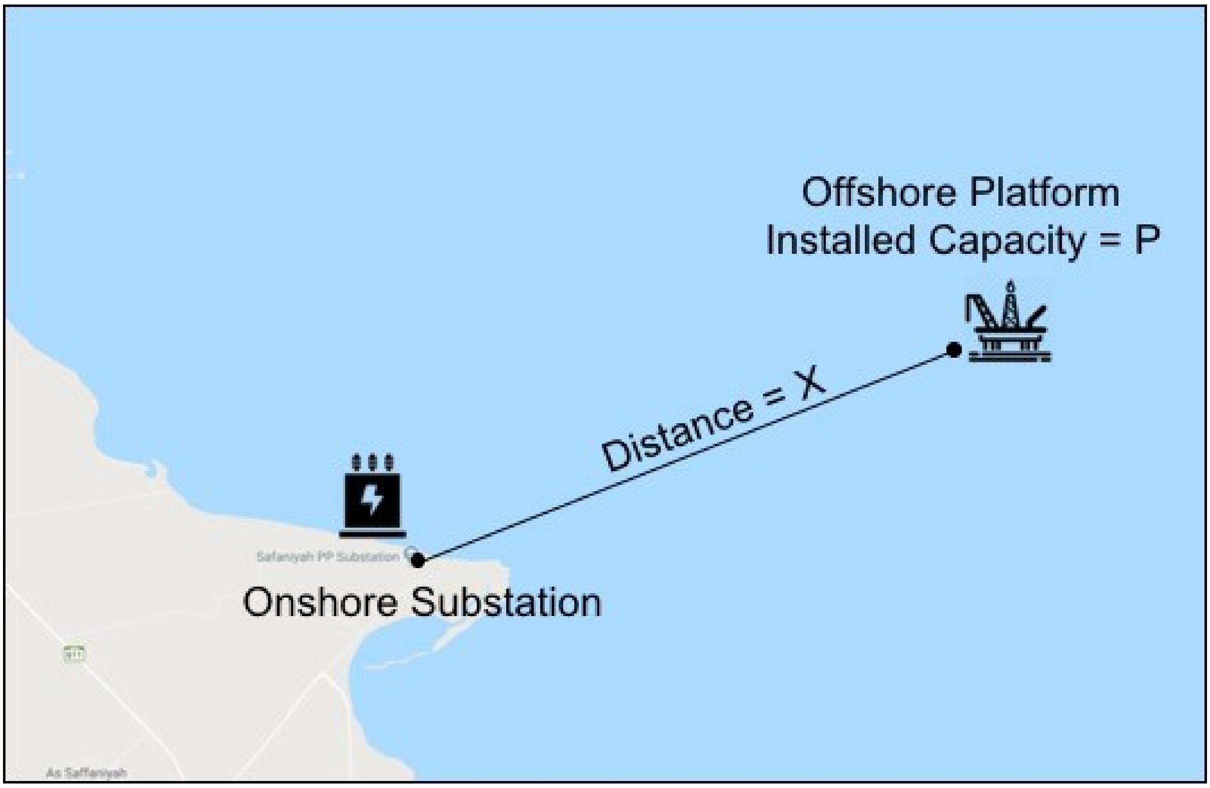

Figure 8.2: Offshore Platform with Varying Distance from Onshore Substation

8.1.2. Algorithm Implementation

The proposed algorithm will be used with minor modification. Figure 8.3 shows the flowchart of finding the optimum technology of defined problem by the distance and installed power of the platform. To find the all solution space set, the proposed algorithm is applied for different scenarios with a range of values of distance and power.

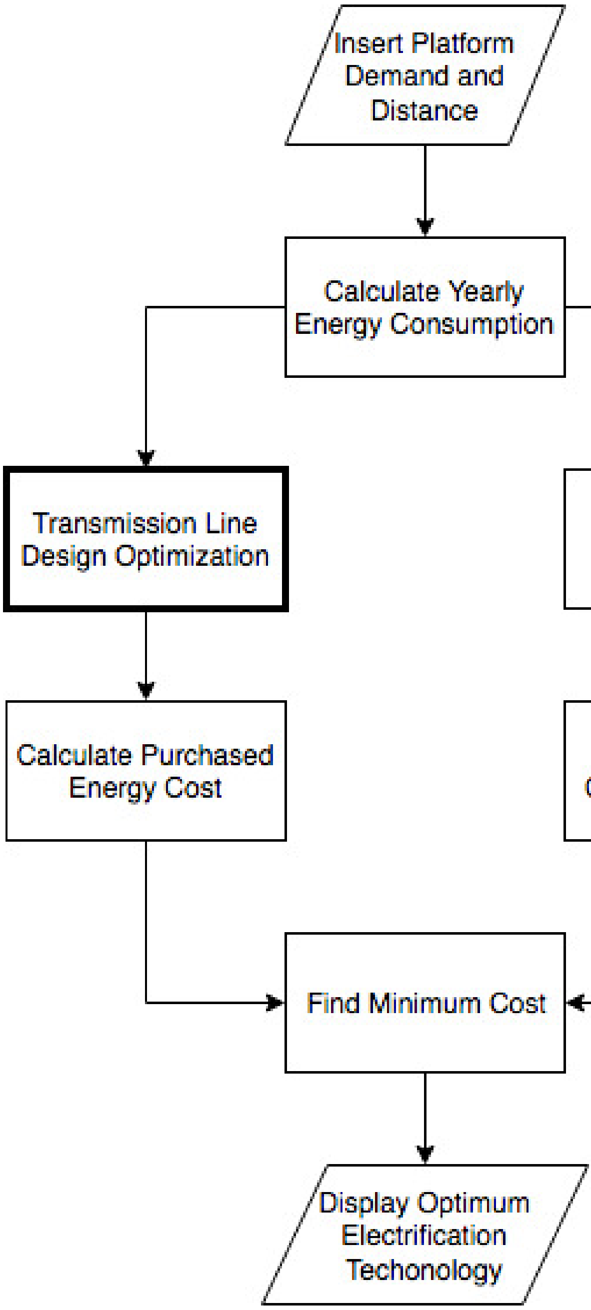

Figure 8.3: The Flowchart of Single Platform Evaluation

8.1.3. Results and Discussion

The results of the algorithm implementation are shown in this section. The considered distance varies from 10 to 400 km, while the installed power varies from 10 to 200 MW. The summary of the algorithm implementation with varying the values of the distance and power capacity is showed in Figure 8.4. The figure shows the technology that has the minimum cost for each case. It shows almost linear cutoff lines of regions, where each region indicates the optimum technology. For example, the figure shows that if the distance is very large it's always feasible to use distributed generation instead of a transmission line. This is expected as increasing the distance will increase the transmission line cost, either HVAC or HVDC. Furthermore, the figure shows that for short distance always using HVAC is more favorable than other technology. But, when either the distance or the power increase, it became more feasible to use HVDC transmission system.

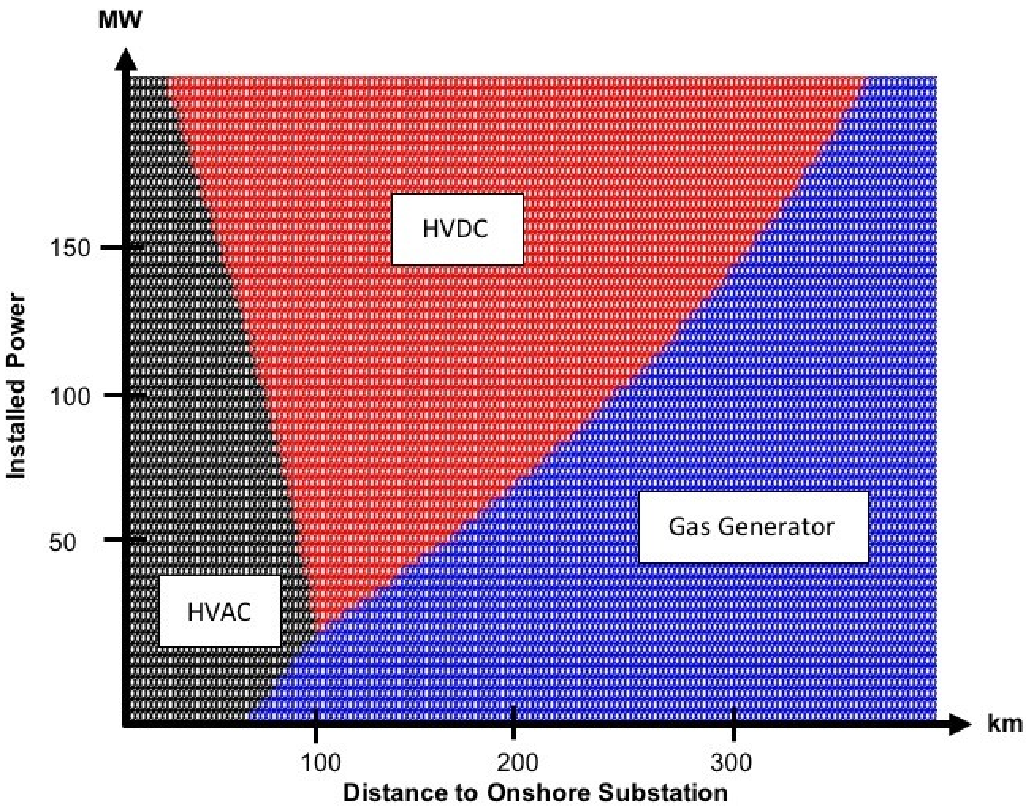

Figure 8.4: Electrificatoin of Single Platform Solution by Techonology

A cross-section area of the plot is considered by selecting a fixed value for the Power equal to 150 MW. This will allow observing the Distance impact on the overall cost. The results are shown in Figures 8.5 – 8.6. At a very close distance, the HVAC transmission line has the lowest cost. There is a change in the slope of the transmission line cost near 90 km, this is due to the cut-off point between HVAC and HVDC transmission systems.

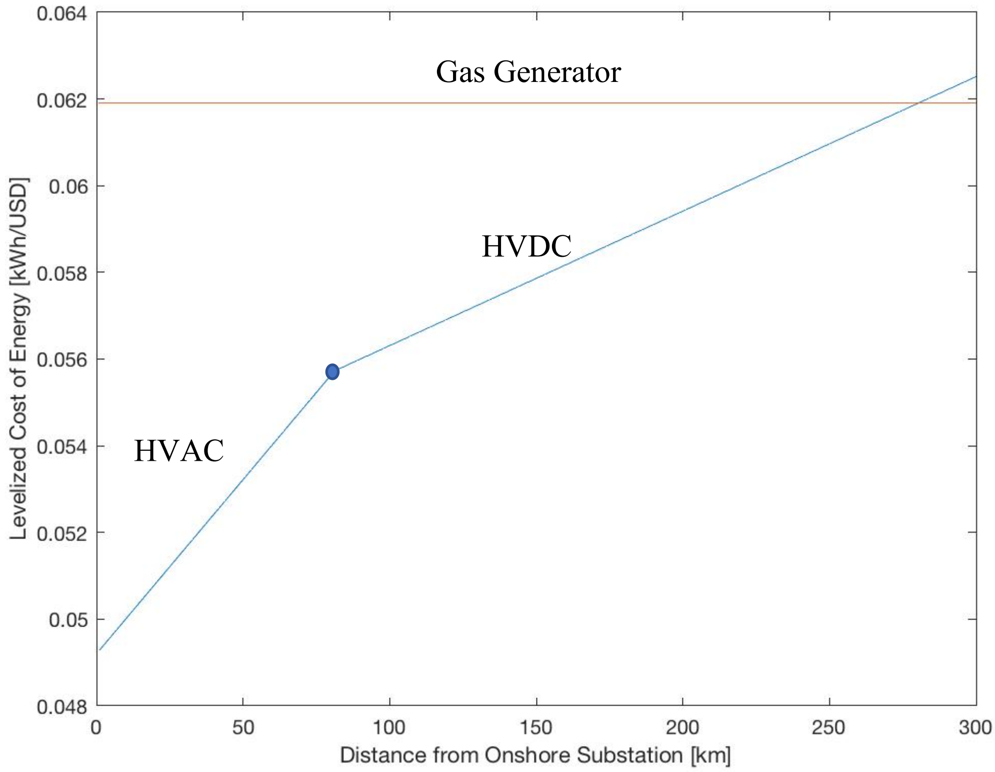

Figure 8.5: Total Cost of Transmission Line with Varying Distance

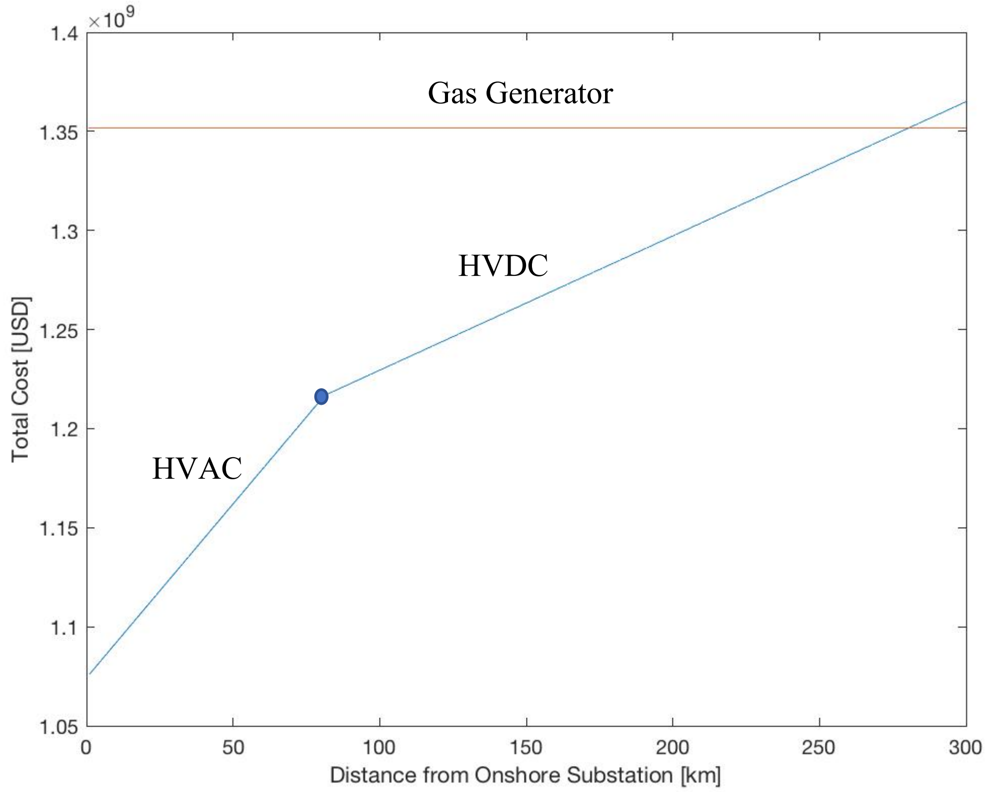

Figure 8.6: The levelized cost of energy (LCOE) of Transmission Line with Varying Distance

The levelized cost of energy (LCOE) for the gas generator is assumed to be constant with respect to the distance. The assumption is justified since the only difference between installing near onshore or far platforms is in the installation cost. The LCOE for the gas generators for 150 MW is calculated to be 0.061 USD/kWh. On the other hand, the LCOE when constructing new transmission line depends on the distance to the nearest onshore substation. As Figure 8.6 shows the LCOE is proportional to the distance starting from 0.049 at a near onshore distance and goes to 0.063 USD/kWh for 200 km far away platforms. Table 8.1 shows the LCOE values at different distance and installed power capacity.

Table 8.1: LCOE of Constructing Transmission Line with Varying Distances and Demands

Installed Power [MW]	Distance from Onshore Substation [km]										
	100	110	120	130	140	150	160	170	180	190	200
50	0.058	0.059	0.060	0.060	0.061	0.062	0.063	0.064	0.065	0.065	0.065
60	0.058	0.058	0.059	0.060	0.061	0.062	0.062	0.063	0.064	0.064	0.065
70	0.057	0.058	0.059	0.060	0.061	0.061	0.062	0.063	0.063	0.064	0.064
80	0.057	0.058	0.059	0.060	0.060	0.061	0.061	0.062	0.062	0.063	0.063
90	0.057	0.058	0.059	0.059	0.060	0.061	0.061	0.061	0.062	0.062	0.063
100	0.057	0.058	0.059	0.059	0.059	0.060	0.060	0.061	0.061	0.061	0.062
110	0.057	0.058	0.058	0.059	0.059	0.059	0.060	0.060	0.061	0.061	0.061
120	0.057	0.058	0.058	0.058	0.059	0.059	0.059	0.060	0.060	0.060	0.061
130	0.057	0.057	0.058	0.058	0.058	0.059	0.059	0.059	0.060	0.060	0.060
140	0.056	0.057	0.057	0.057	0.058	0.058	0.058	0.059	0.059	0.059	0.060
150	0.056	0.057	0.057	0.057	0.058	0.058	0.058	0.058	0.059	0.059	0.059

The reliability of the system is the second objective function. Assessing the system reliability can be using reliability indices of the component. The transmission line reliability indices are shown in Table 8.2 [41], while the FOR of the gas generator is equal 2% [33].

Table 8.2: Reliability Indices of Transmission Line [41]

Component	**Failure Rate (f/yr)**	**Repair Time (h/f)**
HVAC	0.07	24
HVDC	0.1	48

It has been assumed that the average outage time is 48 hours to account for the low maturity level of the system and the low experience of the system operators [29]. The onshore substation availability is assumed to be 0.99%. The LOLP of the power supply of different technology is shown in Table 8.3. Considering the reliability performance, the transmission line option is more reliable. The difference between the HVAC and HVDC technologies is minimal. The difference between the transmission line and the gas generator is estimated to be 0.0095.

Table 8.3: LOLP of Using Each Technology for Single Platform

Technology	**LOLP**	**Availability**
HVAC	0.0102	0.9898
HVDC	0.0105	0.9895
Single Gas Generator	0.0200	0.9800
Two Gas Generators	0.0396	0.9604

8.2. Case Study 2: Practical Case of Electrification of Three Platforms Using Onshore Connection

The developed algorithm is applied to a practical case taken from the field to electrify future offshore platforms using onshore connections. This case is reported in [3] where they want to supply three large offshore loads. In the reference [3] they suggest using HVDC connection to supply the platforms. All the proposed connections are point to point transmission lines connecting the platforms directly to the onshore substation.

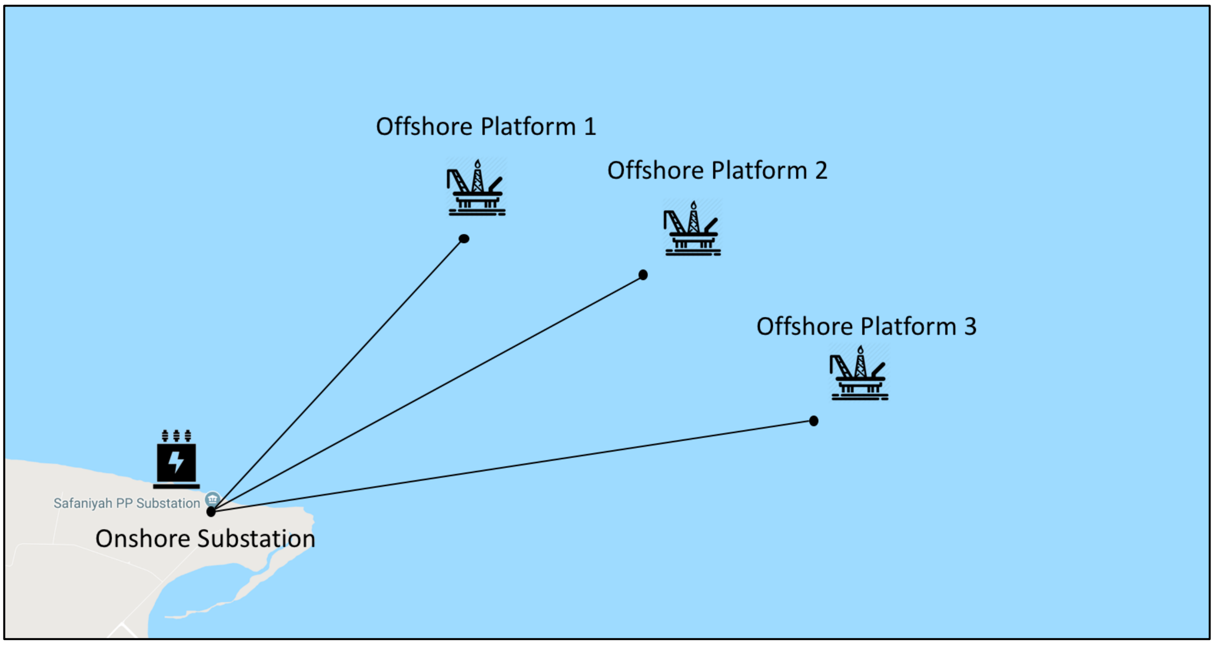

Figure 8.7: Case Study 2 Layout with Three Offshore Platforms

8.2.1. Problem Description

The objective here is to develop a plan to electrify three offshore platforms as shown in Figure 8.7. The coordination and power consumption of the platforms are given as shown in Table 8.4. The transmission line option will be considered first. The solution indicates the transmission line technology, transmission line voltage, and most importantly, the connection topology of the network. The installed power of the offshore platforms and their location are shown in Table 8.4.

Table 8.4: Power Consumption and Location

Description	Installed Power	X Coordinate	Y Coordinate
Offshore Platform 1	100 MW	-10	45
Offshore Platform 2	100 MW	10	70
Offshore Platform 3	100 MW	30	85
Onshore Substation	-	0	0

8.2.2. Algorithm Implementation

To find the optimum solution, the proposed algorithm is implemented with minor additions. The reliability indices data is shown in Table 8.2. The remaining required data is the genetic algorithm. The values used for the genetic algorithm is shown in Table 8.5.

Table 8.5: Genetic Algorithm Parameters

Parameter	Value
Number of Population	40
Stopping Criteria Constant	10
Fittest to be Selected Probability	0.7
BLX-α Crossover Factor	0.5
Mutation Probability	0.1
Non-uniform Mutation Constant	2
Number of Elitism	4

The addition to the original algorithm is to vary the value of Cost of Non-Served Energy (CNSE). It is a similar way of using a weighted sum technique to find Pareto Front [78]. The modified algorithm flowchart is shown in Figure 8.8. Two additional parameters are required in this case. The increment of the CNSE referred to by d, and the maximum CNSE referred to dmax.

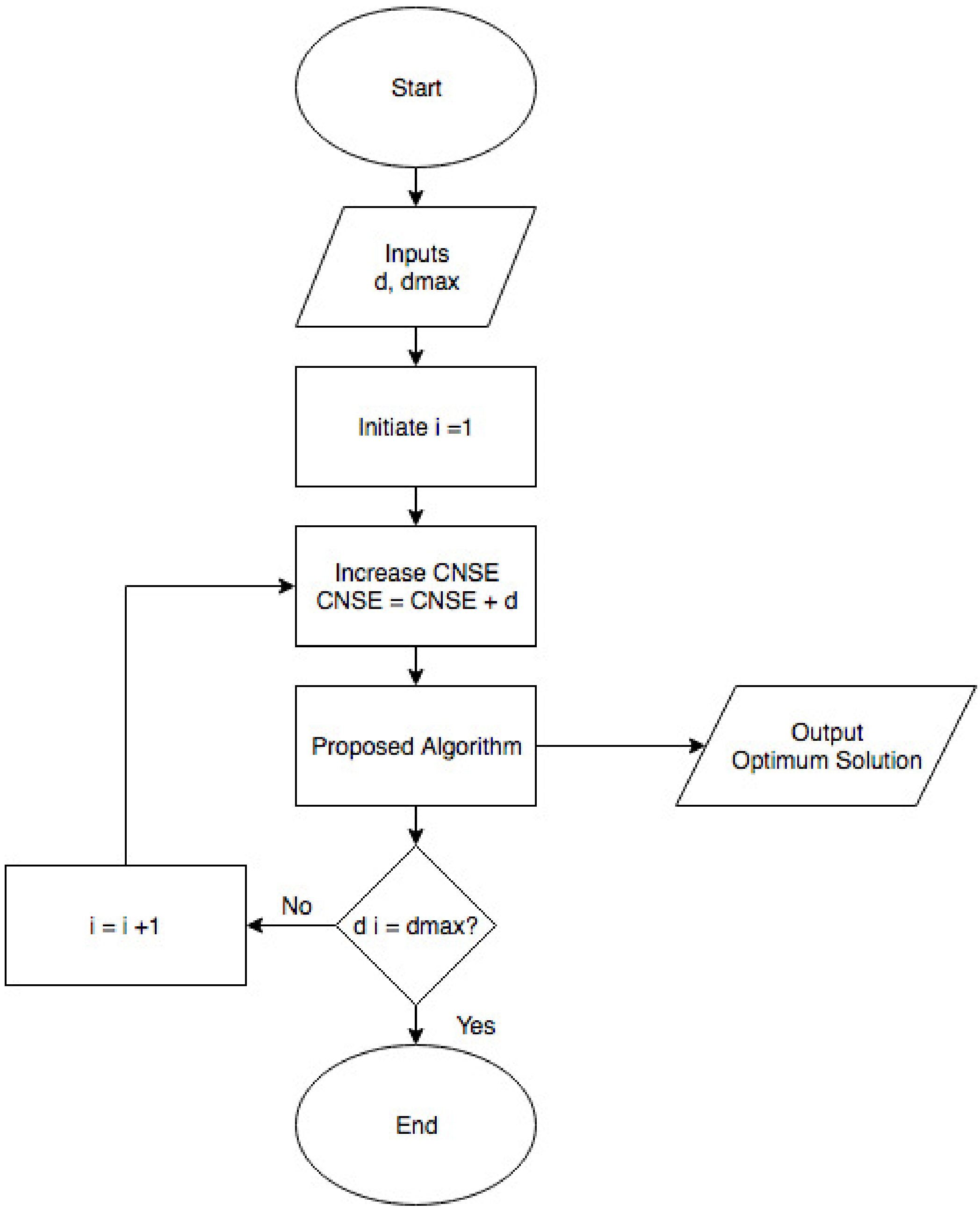

Figure 8.8: Flowchart of Case Study 2 Implementation. The inputs d: is the increment rate of CNSE, and dmax is the maximum CNSE.

8.2.3. Results and Discussion

The results are obtained using the data shown in Table 8.6. The optimum solution details are shown in Figures 8.9 – 8.13. Figure 8.9 shows the Pareto Front solution obtained by varying CNSE. In Figure 8.9, A) Radial, B) Loop, C) Mesh and D) Ring connections are the solution of the optimization. In Figure 8.10 the cost of optimum solutions is shown with step increment. The solution C mesh connection appears six times from the third iteration until the eighth one. The same behavior appears in Figure 8.11 the LOLP. Solution A, the radial connection, has very low reliability comparing to the other solutions. The breakdown cost of the solution C, the loop connection, is shown in Table 8.7. The contribution of each component to the overall cost is shown in Figure 8.12. The component specification of the loop configuration is shown in Table 8.8.

Table 8.6: Input Parameters of Case Study 2

Parameter	**Value [USD/Hour of Interruption]**
Initial CNSE	10,000
Increment Rate (d)	100,000
Maximum CNSE (dmax)	900,000

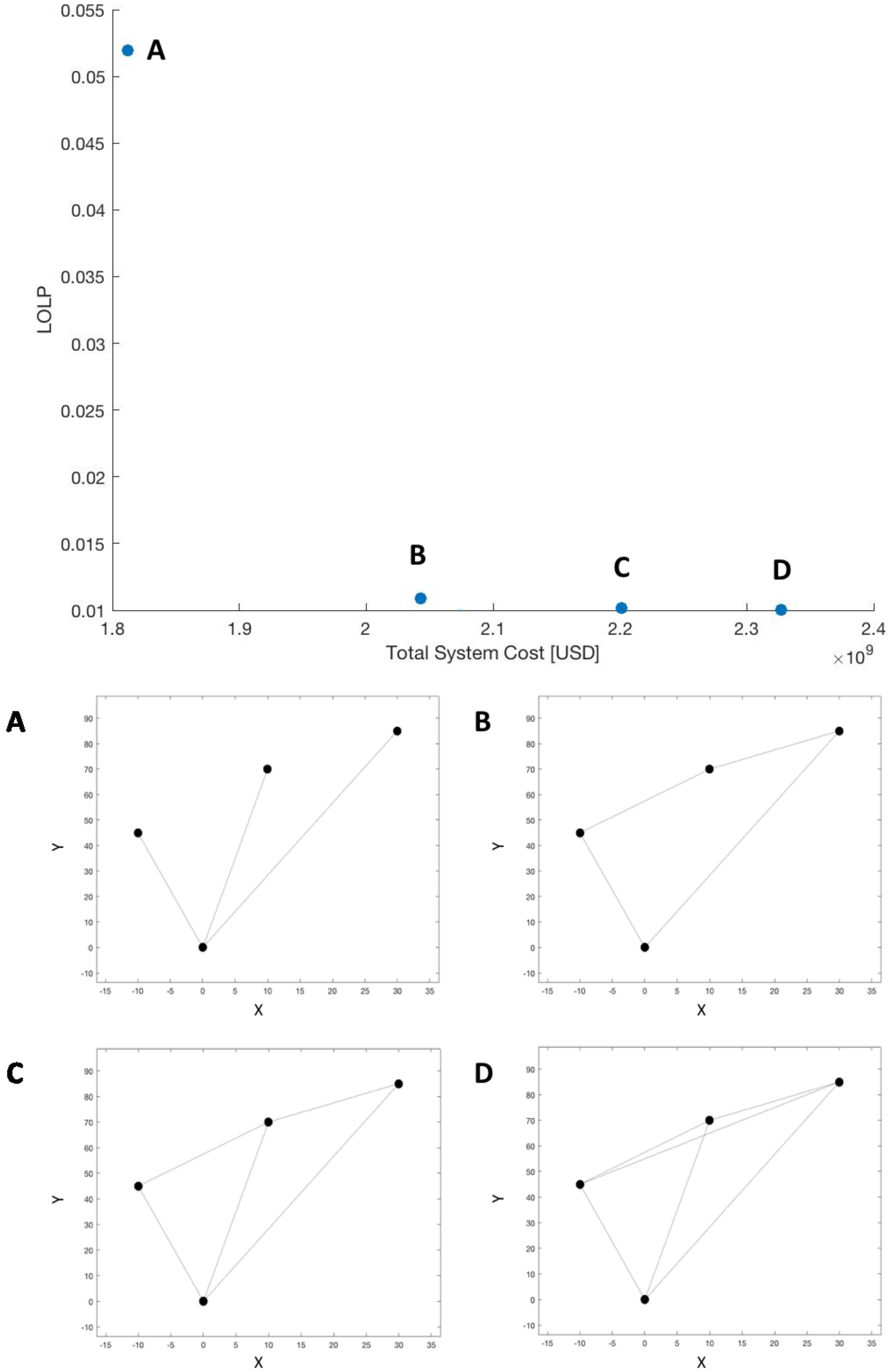

Figure 8.9: Optimum Solutions with Different CNSE Value. The figure in the top shows the solution with respect to the two objective functions. The four figures in the bottom show the layout of those solution.

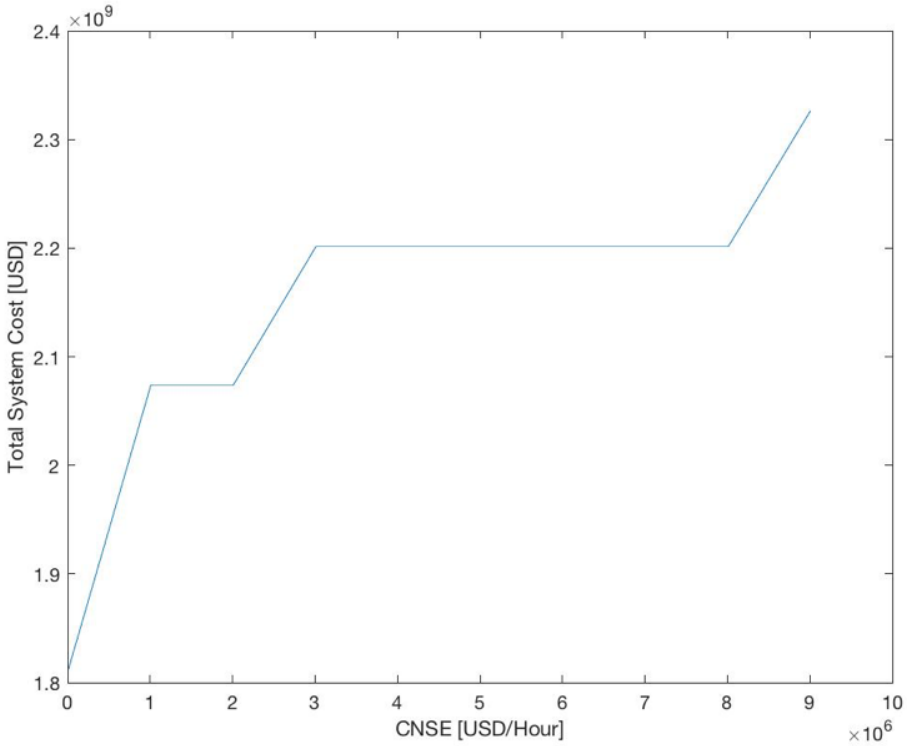

Figure 8.10: Total System Cost of Pareto Front with respect to CNSE

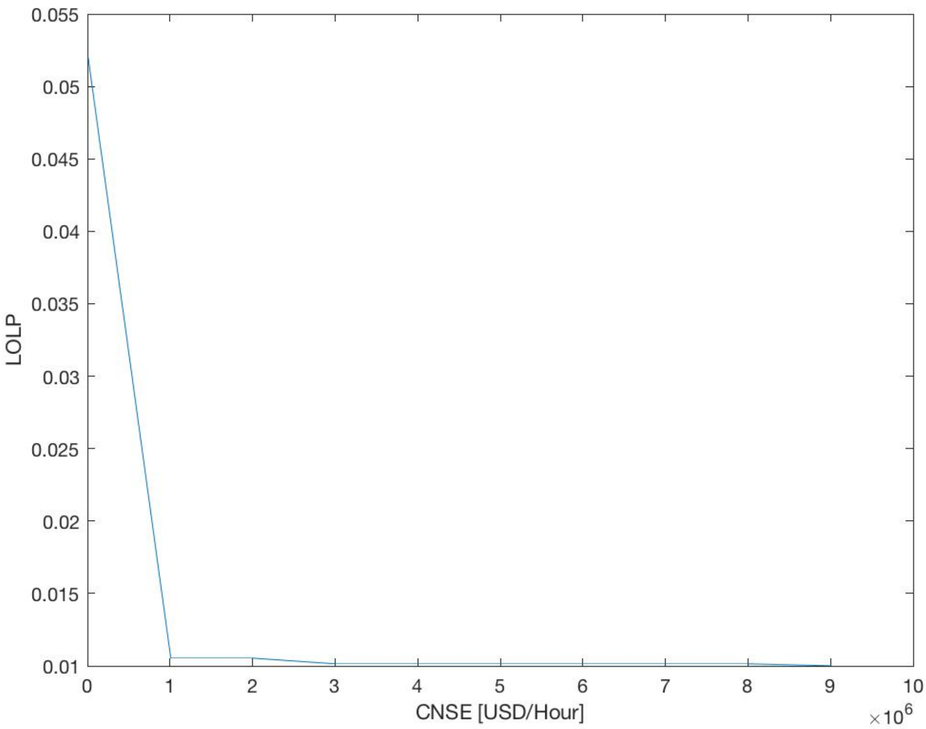

Figure 8.11: LOLP of Pareto Front with respect to CNSE

Table 8.7: Cost Breakdown of the Loop Configuration in MUSD

Component	Transmission Line 1	Transmission Line 2	Transmission Line 3	Transmission Line 4	Total Cost
Cable	15.1	34.2	11.8	66.8	127.9
Switchgear	2.7	2.7	2.7	2.7	10.8
Platform	21.1	30.3	21.1	30.3	102.8
Installation	9.1	13.1	7.1	25.6	54.9
Transformer	2.4	3.3	2.4	3.3	11.4
Compensation	23.8	51.3	18.6	100.3	194
Power Loss	31.9	32.2	24.9	62.9	151.9
Total	106.1	167.1	88.6	291.9	653.7

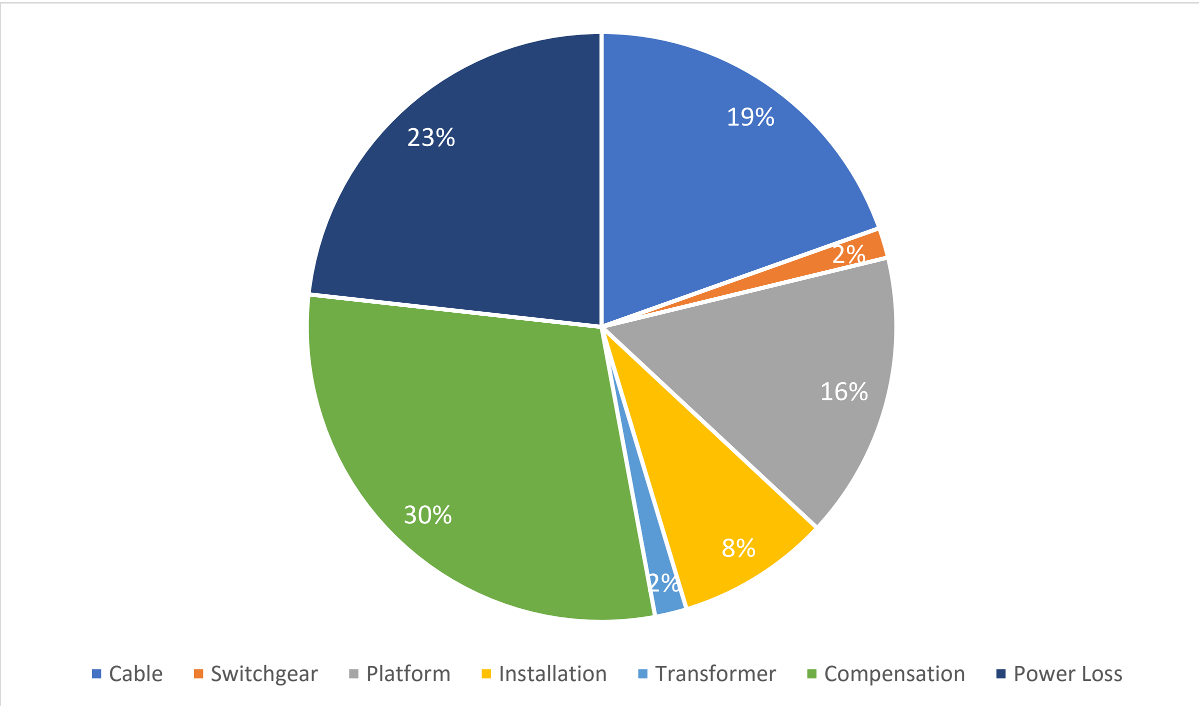

Figure 8.12: Loop System Cost Breakdown per Component

Table 8.8: Component Specification of the Loop Configuration

Component	Transmission Line 1	Transmission Line 2	Transmission Line 3	Transmission Line 4
Power [MW]	200	300	200	300
Voltage [kV]	220	220	220	220
Cable Technology	HVAC	HVAC	HVAC	HVAC
Cable Length [km]	32	46	25	90
Cable Size [mm^2]	300	1000	300	1000

8.3. Case Study 3: Electrification of Three Platforms Using Transmission line and Gas Generators

In this section, the gas generation is included as an additional option. The same problem shown in Case Study 2 will be repeated but with fixed Cost of Non-Served Energy (CNSE). The implementation of the proposed algorithm to an existing system is shown in this section. It has been assumed that all offshore platforms are already supplied by gas generators. The objective is to find the optimum upgrade that ensures optimum reliability and cost balance.

8.3.1. Problem Description

To evaluate the impact of having Gas Generation Units, three scenarios are considered:
Scenario 1) the cost of power loss is fixed to be 500,000 USD for one-hour power loss,
Scenario 2) the cost of power loss is reduced to be 50,000 USD,
Scenario 3) similar to scenario 2 but the platforms are already supplied by Gas Generator units.
The details and the parameters of Case Study 3 are similar to Case Study 1. In addition to that, the power capacity of single Gas Generator unit is assumed to be 25MW. To incorporate the assumption of upgrading existing supply, the capital cost of the Gas Generator units is assumed to be zero and only operation and maintenance cost is included in the calculation.

8.3.2. Results and Discussion

Scenario 1: CNSE = 500,000 USD/Hour

In the first scenario, the objective is to electrify three offshore platforms each with 100 MW. There are three options: either to connected to onshore, or to use distributed generators, or using both onshore connection and distributed generators. The value of CNSE is set to be equal to 500,000 USD/Hour of Interruption. The optimization performance is shown in Figure 8.14. The optimum solution graph is shown in Figures 8.15. The optimum solution doesn't include any distributed generator. All the transmission lines are HVAC with 220 kV.

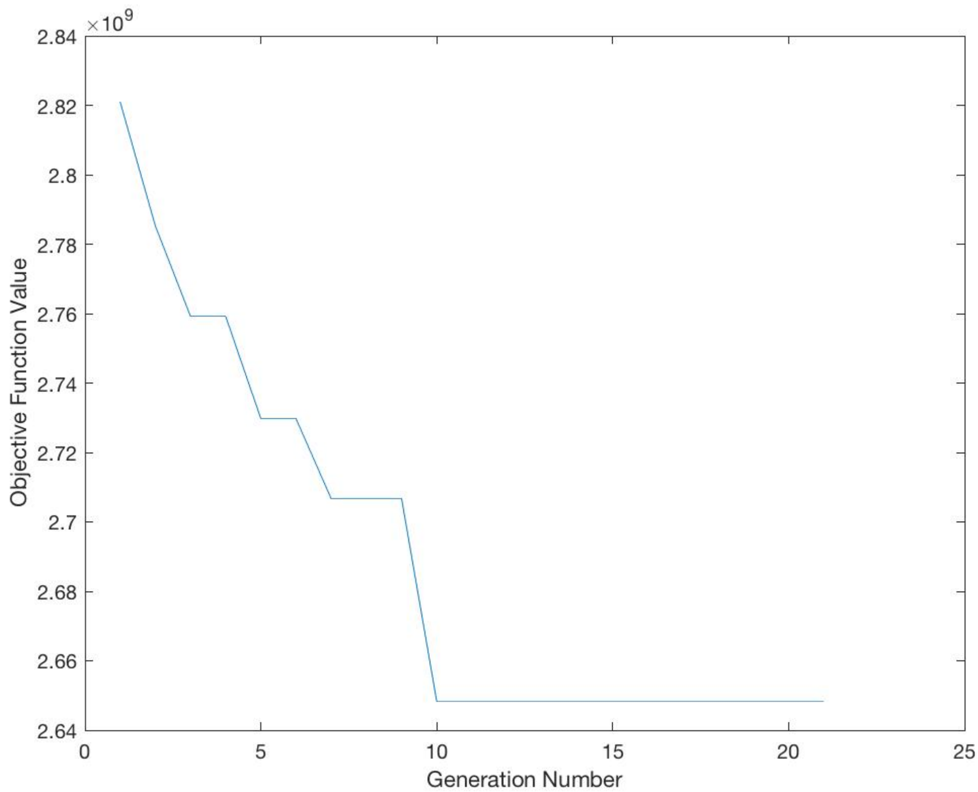

Figure 8.13: Objective Function Performance

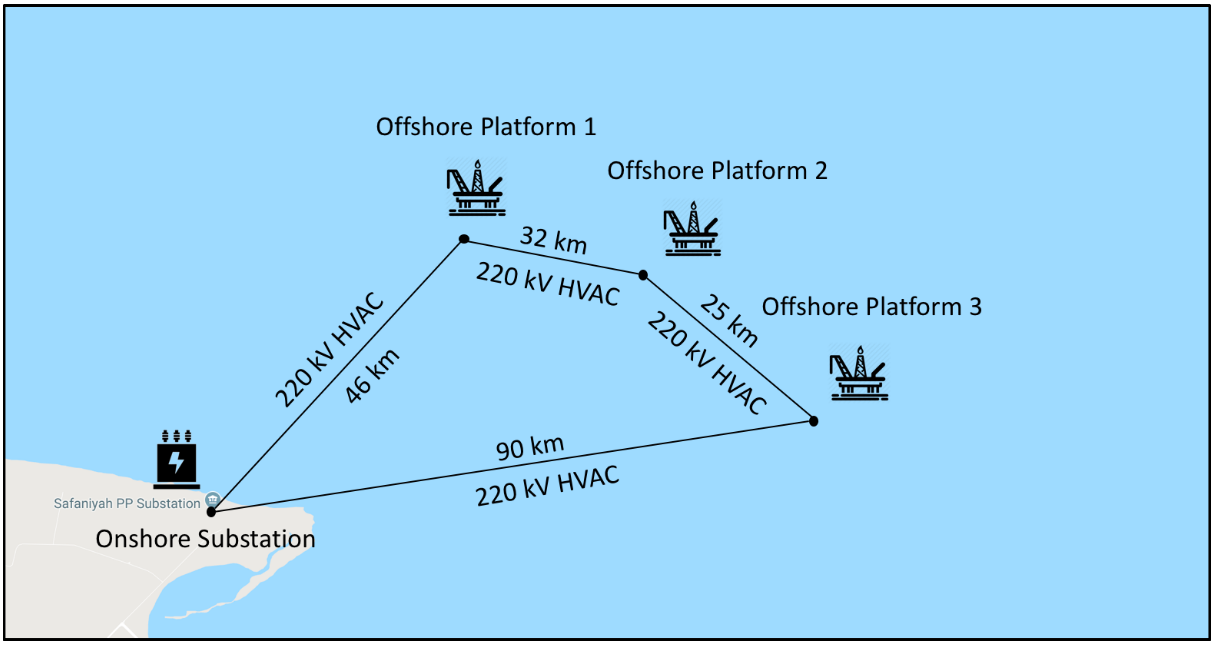

Figure 8.14: Optimum System Layout

Scenario 2: CNSE = 50,000 USD/Hour

In this case, the CNSE is equal to 50,000 USD for each hour of interruption. The optimum solution doesn't include any Gas Generation units. The optimum solution is to have transmission line connected to the onshore substation as shown in Figure 8.16. The system topology is different and less interconnected than the previous case. That is reflected on the LOLP of the optimum design. Where in the first case the LOLP value was 0.0109, while in this case, the LOLP value became 0.015.

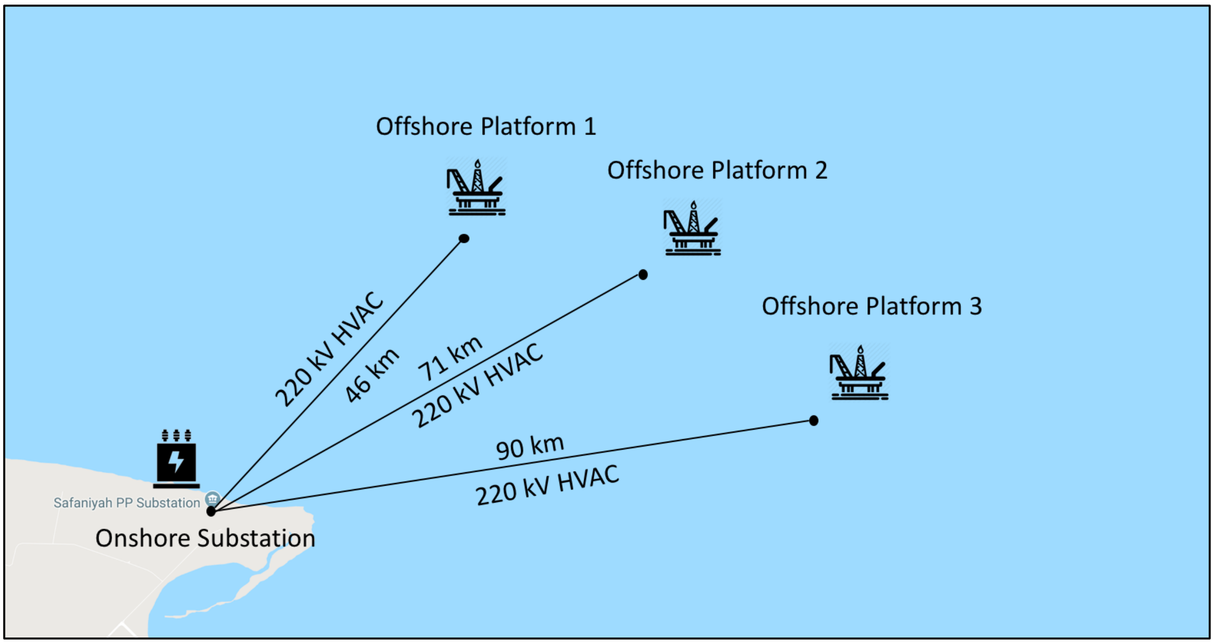

Figure 8.15: Optimum Solution Layout of Scenario 2

Scenario 3: Existing Gas Generators with CNSE = 50,000 USD/Hour

This case considers the existing facilities and. Each platform is supplied by its own gas generators units. The objective now is to upgrade the system to enhance the reliability of the power system. There are two options: 1) keep the existing gas generators as a backup source and pay for the operation and maintenance cost, or 2) to demolish the existing gas generators and use transmission line only. In this case, it has been assumed that no cost is associated with demolishing and the salvage value is also neglected. The solution of this case contains Gas Generation. This implies if the CNSE is low as 50,000 USD/Hour of Interruption, it is more feasible to have a radial connection and use the gas generation as a backup as shown in Figure 8.17.

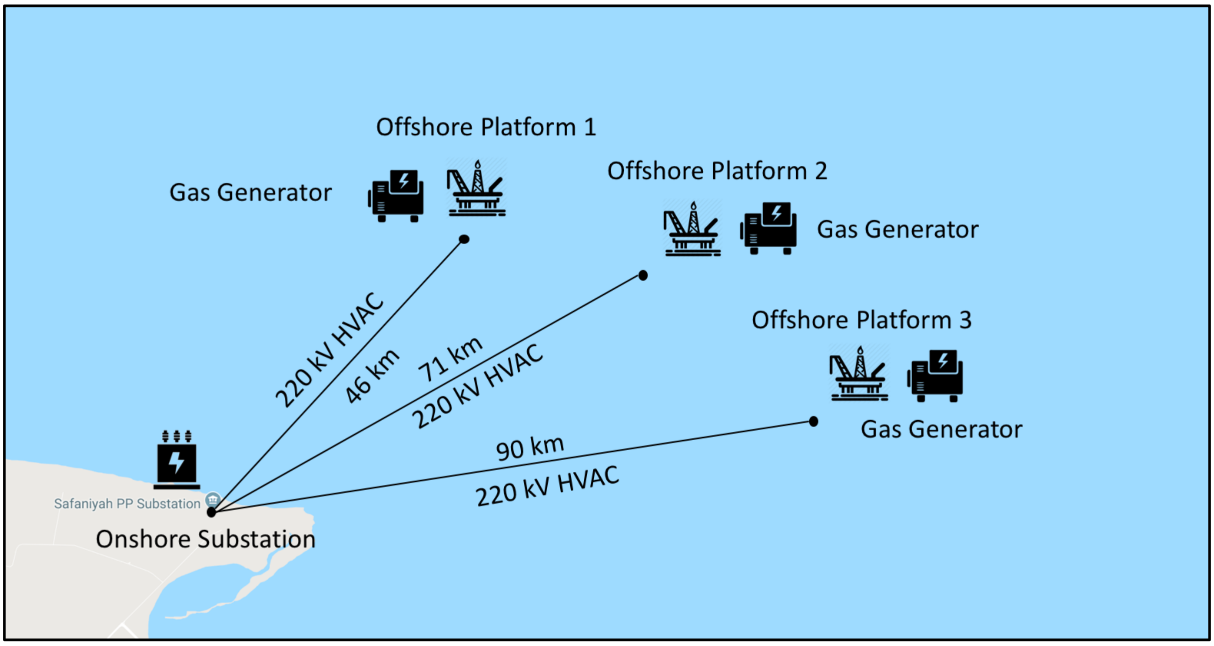

Figure 8.16: The solution layout of the Study Case

The summary of the results of the three scenarios is shown in Table 8.8. If the constraint on the reliability is relaxed the cost of the optimum design decreases. Both the first and second solution doesn't suggest using gas generators units. The difference here is clear in the reliability and cost. The first solution has a higher cost but with high reliability than the second one. In the third scenario, there is existing gas generation installed. The optimum solution implies keeping those generators and connect the platforms to the onshore grid. The different cost is estimated to be 30 MUSD. On the other hand, there is a significant enhancement on the reliability index with 59% reduction on the LOLP.

Table 8.9: Solution Values of Case Study 3 Scenarios

Scenario	**Cost [BUSD]**	**LOLP**	**Configuration**
Scenario 1 (CNSE =500,000 USD)	2.04	0.0109	Loop
Scenario 2 (CNSE =50,000 USD)	1.82	0.0483	Radial
Scenario 3 (CNSE =50,000 USD and Existing DG)	1.85	0.0198	Radial + GG

8.4. Case Study 4: Standby Generator

8.4.1. Problem Description

This case assumes that existing gas generators are installed at the platform. The objective here is to enhance the reliability of the power system with minimum cost. To model this case, the CapEx of the gas generators is eliminated from the calculation. Evaluating the objective function using two topologies, Radial and Loop connections. The value of CNSE to be equal to 500,000 USD/Hour of interruption.

8.4.2. Results and Discussion

The results of implementing the algorithm, in this case, are shown in Table 8.9. The optimum solution is to use loop connection and keeping the existing gas generators as backup. The existing and proposed diagrams are shown in Figure 8.18.

Table 8.10: System Specification with CNSE = 500,000 [USD/Hour]

Configuration	**Cost [BUSD]**	**LOLP**	**Obj. Fun. [x10^{9}]**	**LCOE [USD/kWh]**
Gas Generation*	2.92	0.0115	3.55	0.0892
Radial	1.82	0.0483	4.46	0.0556
Radial with GG	2.06	0.0198	3.14	0.0628
Radial with Existing GG	1.85	0.0198	2.93	0.0565**
Loop	2.04	0.0109	2.64	0.0624
Loop with GG	2.28	0.0073	2.68	0.0695
Loop with Existing GG	2.07	0.0073	2.47	0.0633**

* N-1 contingency is used to evaluate the system

** the value of LCOE doesn't reflect the actual LCOE because the capital cost of existing Gas Generator is not incorporated in the calculation.

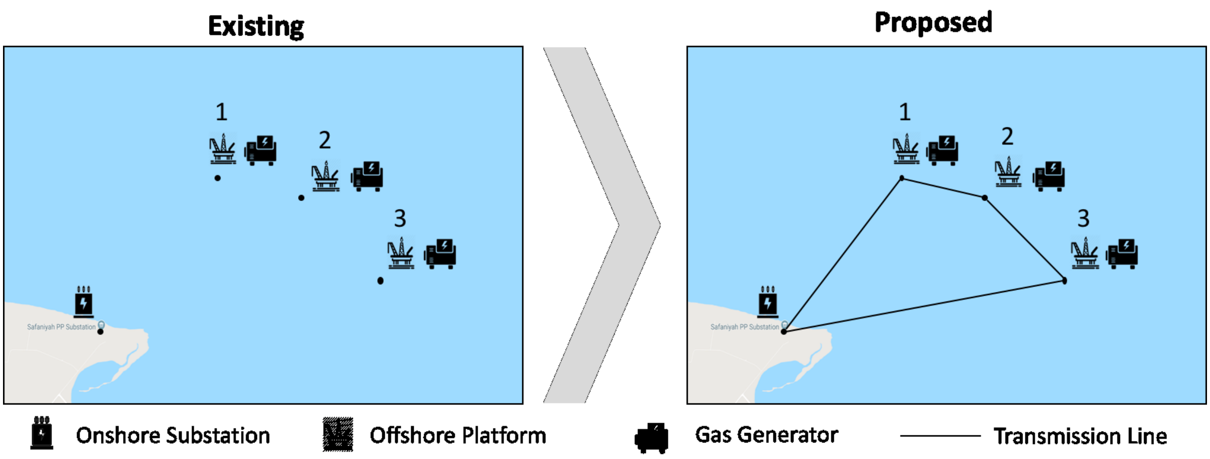

Figure 8.17: Existing and Proposed Layouts of Case Study 4

To further investigate the scenario, the value of CNSE is changed by one magnitude above and below. In the first case, the value of CNSE is set to be as low as 50,000 USD/Hour of Interruption. The optimum solution is to have a radial connection and keep using the existing generators. However, the objective function values are very close from each other. Another solution proposes to select 40% more reliable system by paying 19 MUSD which represents 8% of the total cost.

The last case is when the CNSE is increased to be 1,000,000 USD. In the case, there is a bias towards high reliable solution due to the high CNSE. The optimum solution suggests to use Loop transmission line network and keep using the existing generators. The closest solution to the optimum one is to have Loop connection and demolishing the gas generators. If there are no existing generators at all, the optimum solution is to have Loop connection and install new gas generators as a backup due to the high cost of CNSE. The solution parameters of the two cases are shown in Tables 8.10 and 8.11. A comparison of those two cases and the base case is shown in Figure 8.19 and Table 8.12, the optimum solutions are highlighted in the table. All the solutions of the case when CNSE equal 50,000 USD are shown in Figure 8.20. The solutions are ordered from the top the most optimum solution to bottom the worst solution.

Table 8.11: System Specification with CNSE = 50,000 USD/Hour

Configuration	**Cost [BUSD]**	**LOLP**	**Obj. Fun. [x10^9]**	**LCOE [USD/kWh]**
Radial	1.82	0.0483	2.08	0.0556
Radial with DG	2.06	0.0198	2.16	0.0628
Radial with Existing DG	**1.85**	**0.0198**	**1.96**	**0.0565***
Loop	2.04	0.0109	2.10	0.0624
Loop with DG	2.28	0.0073	2.31	0.0695
Loop with Existing DG	2.07	0.0073	2.11	0.0633*

Table 8.12: System Specification with CNSE = 1,000,000 USD/Hour

Configuration	**Cost [BUSD]**	**LOLP**	**Obj. Fun. [x10^9]**	**LCOE [USD/kWh]**
Radial	1.82	0.0483	7.09	0.0556
Radial with DG	2.06	0.0198	4.22	0.0628
Radial with Existing DG	1.85	0.0198	4.01	0.0565*
Loop	2.04	0.0109	3.23	0.0624
Loop with DG	2.28	0.0073	3.08	0.0695
Loop with Existing DG	**2.07**	**0.0073**	**2.87**	**0.0633***

Table 8.13: Objective Function Value with Different CNSE USD/Hour

CNSE [USD/Hour]	**50,000**	**500,000**	**1,000,000**
Radial	2.08	4.46	7.09
Radial with DG	2.16	3.14	4.22
Radial with Existing DG	1.96	2.93	4.01
Loop	2.10	2.64	3.23
Loop with DG	2.31	2.68	3.08
Loop with Existing DG	2.11	2.47	2.87

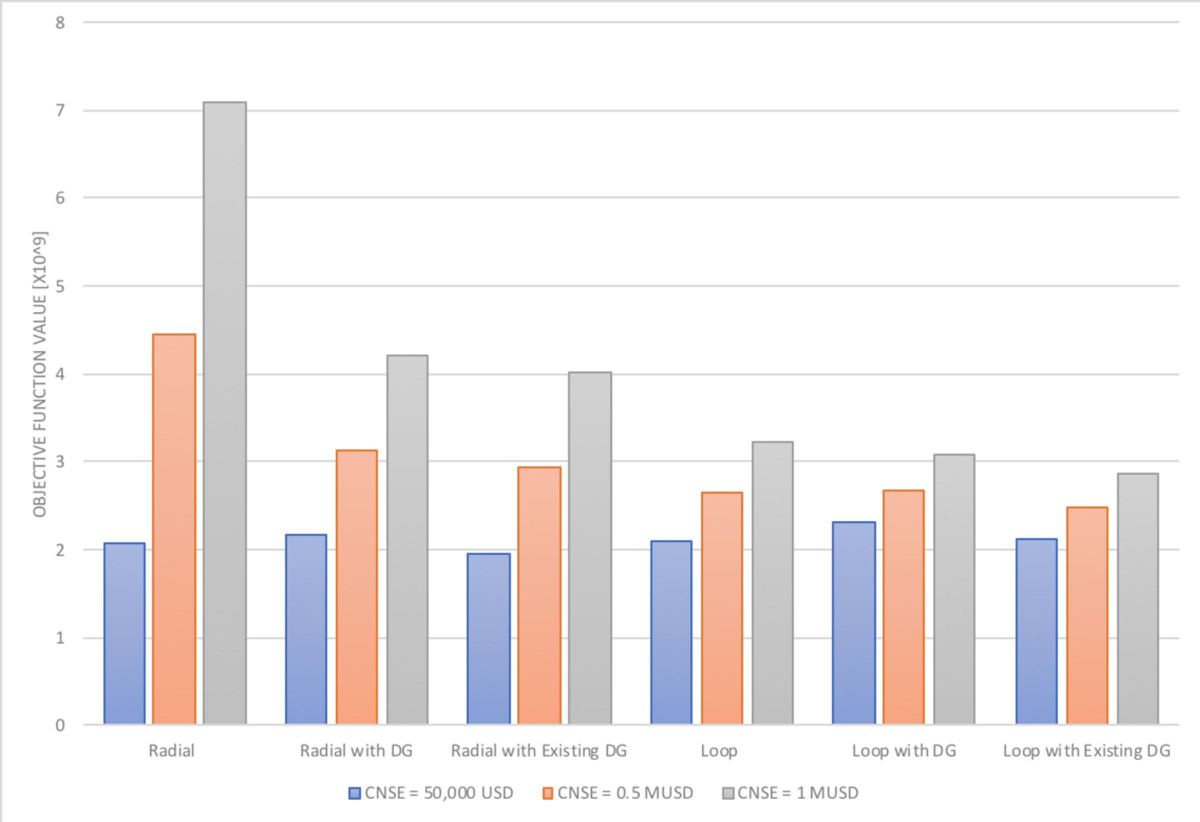

Figure 8.18: The Objective Function Values of Different Configurations and CNSE

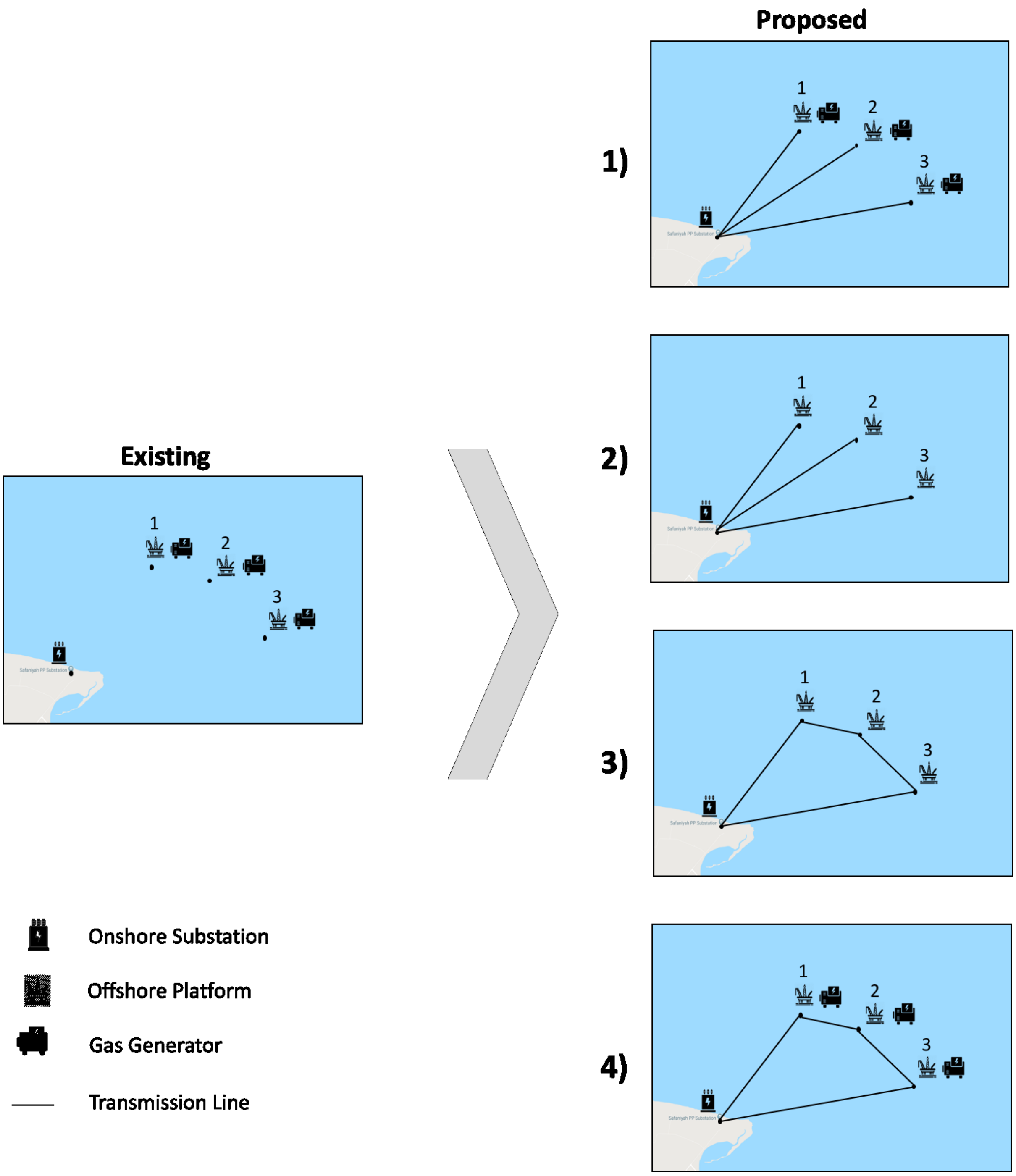

Figure 8.19: The Existing and Proposed Plan for the Case CNSE = 50,000 USD/Hour. The left figure shows the existing installation. The right figures show the proposed optimum plan in order, the first mean most optimum.

8.5. Case Study 5: Introducing Wind to Generation Mixture

8.5.1. Problem Description

The objective, in this case study, is to study the impact of introducing the renewable distributed generation to the supply mix. The Cost of Non-Served Energy (CNSE) is set to be 50,000 USD/Hour of Interruption. The wind speed data are taken from simulation tool proposed in [79] for an offshore area at the Arabian Gulf near the Saudi Arabia east coast at 120 meter height. The average wind speed is quite low. The locations are well known to have large offshore oil and gas fields. The average wind speed is 6 m/s, and the capacity factor of the wind system is 29%. The wind speed data is shown in Figure 8.21.

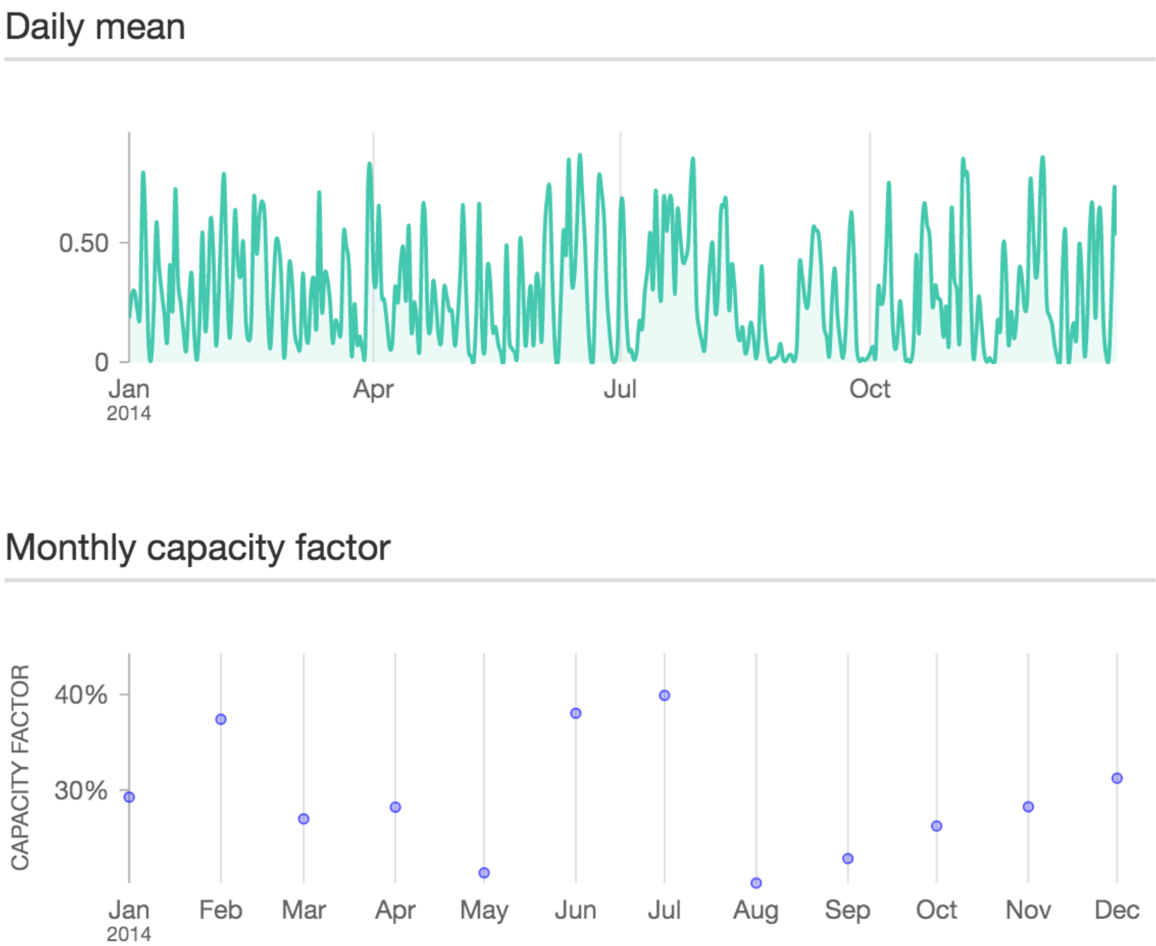

Figure 8.20: Wind Speed data for a Location at Arabian Gulf

8.5.2. Results and Discussion

The proposed algorithm is used to find the optimum solution, after addition wind turbine as one of the options. It has been found that the renewable resources are an unfeasible option in term of reliability and cost-effectiveness. All the proposed solutions don't include wind turbines in the solutions.

To study the impact of using a wind system, three systems configurations are considered with wind system. The capacity of the wind system is assumed to be 100 MW at each location. The wind turbine specification is obtained from [80]. The capacity of a single wind turbine is 5MW and the rotor diameter is 158 m. The hub height is assumed to be 120 m. The objective function has been evaluated for the three cases with and without wind system. The results of the evaluation are shown in Table 8.13. In the same table, the LCOE of the wind system is calculated using the generated wind energy and the cost of wind system. In that case, the LCOE of the wind system is very high compared to the original system LCOE. Moreover, the reliability enhancement after adding wind turbines are captured in Table 8.14. The enhancement is insignificant in the other three cases.

Table 8.14: LOCE with and without Wind Energy

Configuration	**LCOE Without Wind [USD/kWh]**	**LCOE With Wind [USD/kWh]**
Radial	0.0556	0.0931
Loop	0.0624	0.0999
Mesh	0.0672	0.1047

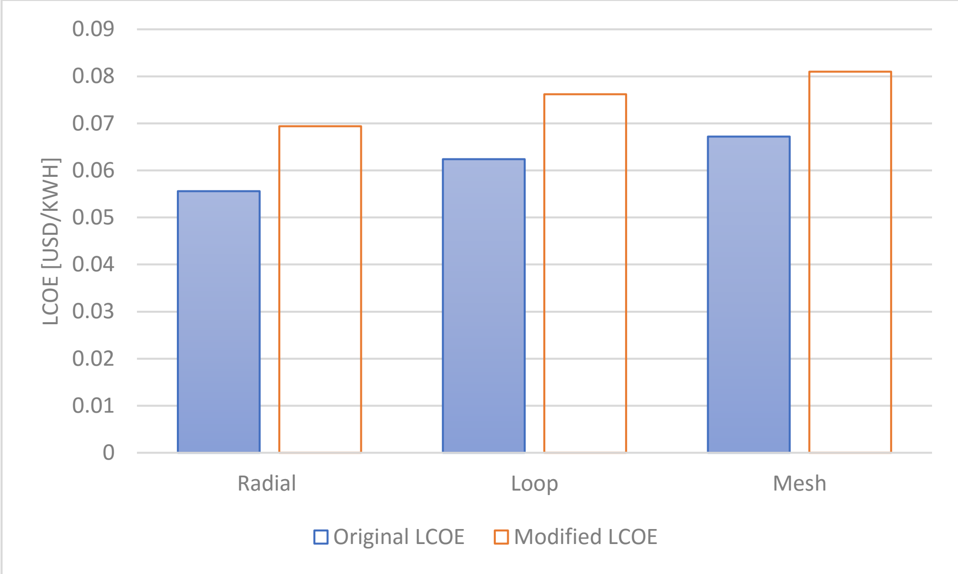

Figure 8.21: LOCE without and with Wind Energy

Table 8.15: LOLP with and without Wind Energy

Configuration	LOLP Without Wind	LOLP With Wind
Radial	0.0483	0.0480
Loop	0.0109	0.0108
Mesh	0.0101	0.0101

Table 8.16: Cost Breakdown of the Radial Configuration in BUSD

Component	Radial without Wind [BUSD]	Radial with Wind [BUSD]
Transmission Lines	0.239	0.239
Wind System	0	1.77
Energy Cost	1.57	1.04
Total	1.82	3.05

The same exercise repeated at a different location. The wind speed data are for offshore location at the North Sea in Europe, which is also known to have huge oil fields. The wind speed at the new location is higher than the previous case. The average wind speed is 11 m/s and power capacity of the wind system is calculated to be 62%. The wind speed data is shown in Figure 9.23. The outcome of evaluating the objective function is shown in Table 8.16 and

Figure 8.24. The LCOE of the modified system is much lower from the previous case. Moreover, the LCOE of wind turbines is very close to the original system LCOE. In the mesh case, the LCOE of wind turbines is lower than the original system. However, the modified system LCOE is still higher than the original system.

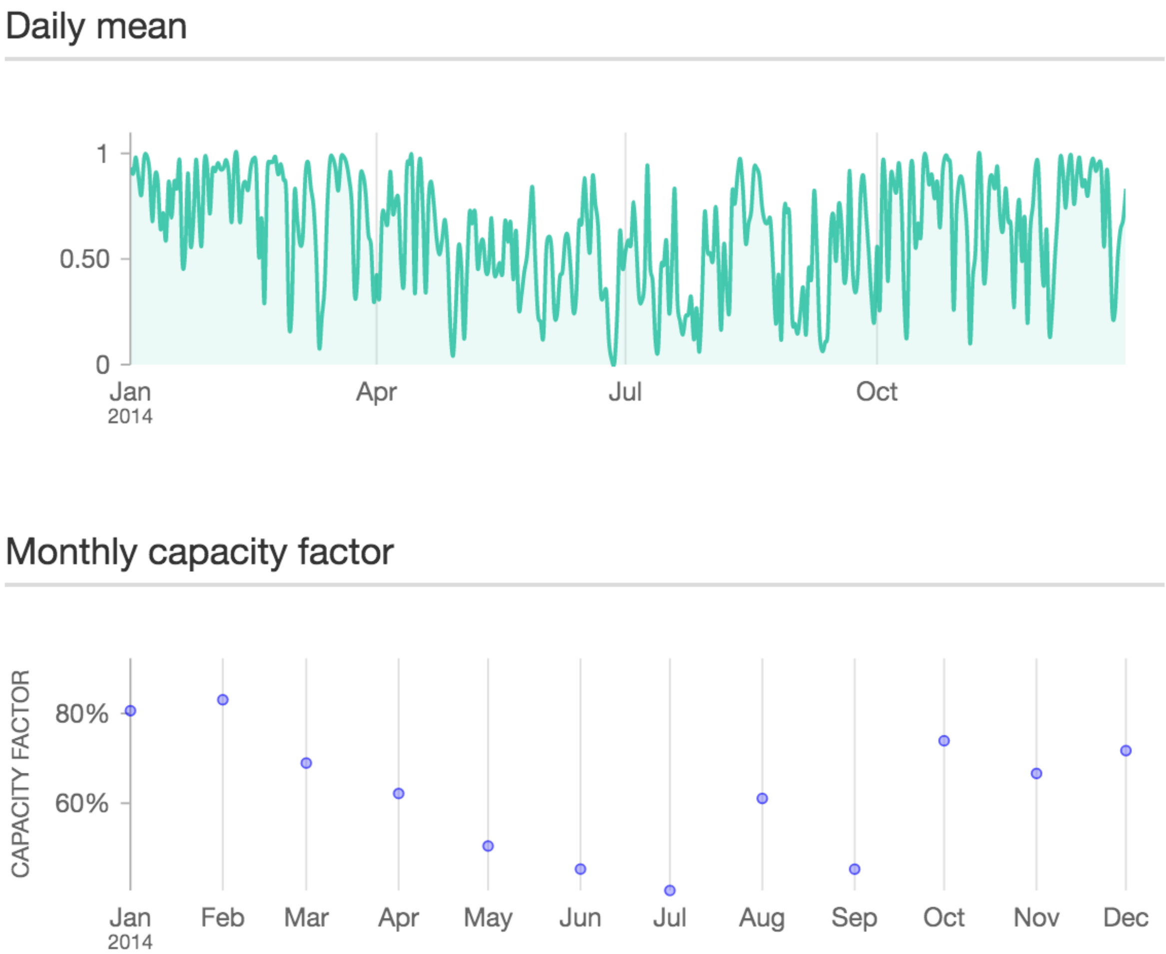

Figure 8.22: Wind Speed Data for a Location at North Sea

Table 8.17: LCOE with and without Wind Energy

Configuration	**LCOE Without Wind [USD/kWh]**	**LCOE With Wind [USD/kWh]**
Radial	0.0556	0.0694
Loop	0.0624	0.0762
Mesh	0.0672	0.0810

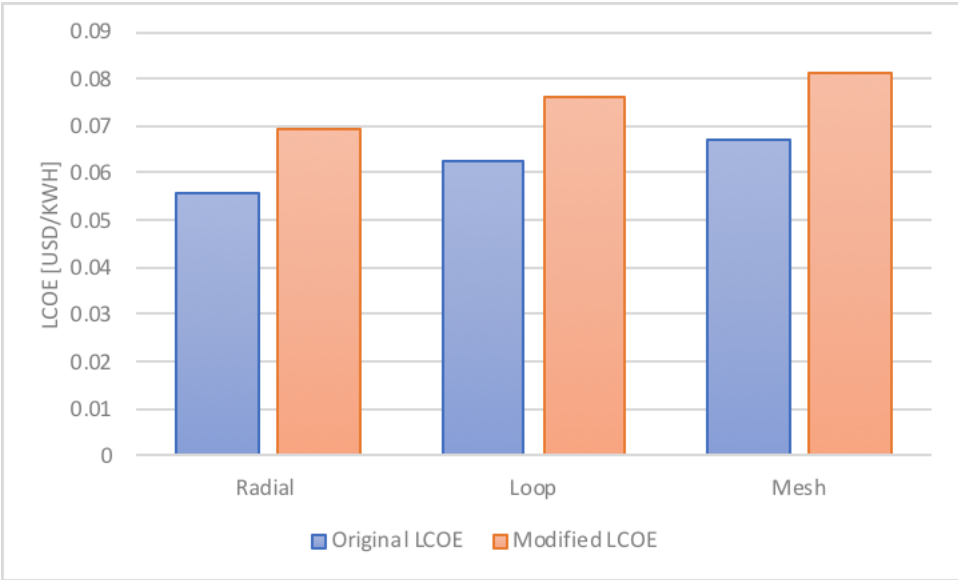

Figure 8.23: LOCE with and without Wind Energy

Although the LCOE of wind turbine alone is lower than the original system, the LCOE of the new system is higher. This is due to the large increase in the CapEx while the amount of energy is the same. This increment is significant in the mesh case because it has more CapEx involved to construct the mesh network. Moreover, the enhancement in the reliability is not significant comparing to introducing Gas Generator. Installing Wind Generator increases the total cost of the system even if the LCOE of the wind is less as in the mesh case.

CHAPTER IX

CONCLUSION

The electrification problem off offshore platforms has been explained in details. The special thing about the offshore platform is the criticality of the load. Where a minor outage could cause huge loss of revenues. Hence, the objective is not focused on the system cost, but also it incorporates the reliability of the power supply. A new algorithm has been developed to solve the problem and provide optimum solutions that satisfy the objective of the problem, the lowest cost with the highest reliability. Several mathematical concepts and state-of-art techniques used within the proposed algorithm such as; Bayesian Network, Minimal Tie-set, Genetic Algorithms, Regression Analysis and Nelder Mead Method.

The proposed algorithm is designed to help decision-makers to achieve better decisions based on mathematical optimization. The proposed tool architecture contains three layers:

- User Interface where the user inserts inputs and change optional parameters,
- Proposed Algorithm run in the background to find the optimum solutions, and
- Output Layer to display the optimum system specification and some statistics about it.

The Cost of Non-Served Energy (CNSE) plays a major role in the optimization process. The user of the tool shall decide and value the load criticality carefully to set CNSE. The higher the value the more the output is reliable and the more the system cost.

The most common feasible solutions are four: Radial, Loop, Mesh, and Ring Connections. The lower CNSE the more likely to lean towered Radial connection. An interesting case has been discussed is when there is a power supply exist at the platform and the objective is to upgrade the power system to enhance the reliability. The algorithm shows that the answer will be different depends on how much is CNSE. In some cases, it’s better to keep using the existing generators as standby to enhance the reliability. Other cases suggested demolishing those generators to reduce the operation cost.

Introducing wind system doesn't improve the system cost nor reliability. In fact, the wind system will increase the overall cost, and the enhancement in the reliability of the system is minimal. Wind energy provides cleaner energy and this is the main motivation to install wind systems.

Many recommendations can be derived from implementing the proposed algorithm. Some of the main recommendations can be summarized as the following:

- The oil and gas companies should value their field and estimate the CNSE to have better decision to electrify their offshore facilities.
- The existing facilities must be considered in the upgrade planning stage, as they could be part of the optimum solution. However, their existence doesn't imply using them is always a feasible solution.

There are many areas of improvement can be added to the proposed algorithm. The following ideas could be used to further enhance the algorithm:

- Applying different optimization algorithm rather than the genetic algorithm used in the proposed method. One of the major drawbacks of the genetic algorithm is the execution time. Mathematical or Artificial optimization can be used to verify the results and compare their performance.
- Enhancing the computation time. This could be achieved by optimizing the code and parallelize the computation. A clear bottle nick encountered at the reliability assessment model. The computation time of the reliability assessment can be optimized by applying network theory algorithms such as fast minimal tie set algorithm and using variable elimination to calculate the probability of the Bayesian Network.
- Including more technologies. Only four technologies are included in the optimization. More solution can be investigated and added to the mix such as PV, Diesel Generation on the generation side, Line Commuting Current HVDC and Low-Frequency Alternative Current (LFAC) in the transmission line side.
- More accurate cost model. A further investigation can be made to enhance the cost model. The more the data is recent the more accurate the model is. Moreover, some of the cost model components are affected by some scenario specific variation. Where each scenario might have some variation depends on the actual site, logistics issues, and technology availability.

- Generalize the Algorithm. The proposed algorithm can be modified to be more general for any electrification problem. This can be done by taking more technology into consideration, updating the cost and reliability assessment models' parameters.
- Add value for clean energy. This will give an advantage of using renewable generation. In fact, many counties around the world imposed taxed on the excess Carbon Dioxide (CO_2) emissions. Adding this value into the calculation might promote using renewable energy resources.

Finally, the outcome of this study has been developed and coded for a specific case discussed in this thesis. The code can be optimized and wrapped into User Interface (UI) as a tool to be used to solve offshore platform optimization problem.

REFERENCES

[1] Ergun, H.; Van Hertem, D.; Belmans, R., "Transmission System Topology Optimization for Large-Scale Offshore Wind Integration," Sustainable Energy, IEEE Transactions on , vol.3, no.4, pp.908,917, Oct. 2012.
[2] P. Bresesti , W. Kling , R. Hendriks and R. Vailati "HVDC connection of offshore wind farms to the transmission system", IEEE Trans. Energy Convers., vol. 22, no. 1, pp.37 -43 2007.
[3] Al-Haiki, Z.E.; Shaikh-Nasser, A.N., "Power transmission to distant Offshore facilities," in Petroleum and Chemical Industry Conference, 2009. PCIC 2009. 2009 Record of Conference Papers - Industry Applications Society 56th Annual , vol., no., pp.1-5, 14-16 Sept. 2009.
[4] Chris Lo, "Onshore Power for Offshore Platforms," Offshore Technology Website, July 2014. https://www.offshore-technology.com/features/featureonshore-power-for-offshore-platforms-4330517/
[5] Horle, N.; Maeland, A., "Electrical supply for offshore installations made possible by use of VSC technology," Presented at Cigré 2002 Conference, Paris, France, Aug 2002.
[6] G. Shi, S. Peng, X. C., Zhe Chen and Wei He, "Grid integration of offshore wind farms and offshore oil/gas platforms," Power Electronics and Motion Control Conference (IPEMC), 2012 7th International, Harbin, China, 2012, pp. 1301-1305.
[7] Jorun I. Marvik, Eirik V. Øyslebø, Magnus Korpås, Electrification of offshore petroleum installations with offshore wind integration, Renewable Energy, Volume 50, February 2013, Pages 558-564, ISSN 0960-1481, http://dx.doi.org/10.1016/j.renene.2012.07.010.
[8] Valentina Orlandini, Leonardo Pierobon, Signe Schløer, Andrea De Pascale, Fredrik Haglind, Dynamic performance of a novel offshore power system integrated with a wind farm, Energy, Volume 109, 15 August 2016, Pages 236-247, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2016.04.073.
[9] Magnus Korpås, Leif Warland, Wei He, John Olav Giæver Tande, A Case-Study on Offshore Wind Power Supply to Oil and Gas Rigs, Energy Procedia, Volume 24, 2012, Pages 18-26, ISSN 1876-6102, http://dx.doi.org/10.1016/j.egypro.2012.06.082.

[10] M. L. Kolstad, K. Sharifabadi, A. R. Årdal and T. M. Undeland, "Grid integration of offshore wind power and multiple oil and gas platforms," 2013 MTS/IEEE OCEANS - Bergen, Bergen, 2013, pp. 1-7. doi: 10.1109/OCEANS-Bergen.2013.6608004

[11] M. L. Kolstad, K. Sharifabadi, ` A. R. Årdal and T. M. Undeland, "Grid integration of offshore wind power and multiple oil and gas platforms," 2013 MTS/IEEE OCEANS - Bergen, Bergen, 2013, pp. 1-7. doi: 10.1109/OCEANS-Bergen.2013.6608004

[12] S. Sanchez, E. Tedeschi, J. Silva, M. Jafar and A. Marichalar, "Smart load management of water injection systems in offshore oil and gas platforms integrating wind power," in IET Renewable Power Generation, vol. 11, no. 9, pp. 1153-1162, 7 12 2017.

[13] Speight, J. G., "Handbook of Offshore Oil and Gas Operations," Gulf Professional Publishing, 2014.

[14] K. Rajashekara, H. S. Krishnamoorthy and B. S. Naik, "Electrification of subsea systems: requirements and challenges in power distribution and conversion," in CPSS Transactions on Power Electronics and Applications, vol. 2, no. 4, pp. 259-266, December 2017.

[15] P. Nallagownden and A. D. Alias, "Power system studies for reliable operation of an offshore platform," Power Engineering and Optimization Conference (PEOCO), 2010 4th International, Shah Alam, 2010, pp. 261-266.

[16] Myhre, J. C., "Electrical Power Supply to Offshore Oil Installations by High Voltage Direct Current Transmission," Master Thesis, Norwegian University of Science and Technology, Department of Electrical Power Engineering, Apr. 2001.

[17] M. J. Thompson, A. Li, R. Luo, M. C. Tu and I. Urdaneta, "Advanced synchronizing systems improve reliability and flexibility of offshore power systems," 2015 IEEE Petroleum and Chemical Industry Committee Conference (PCIC), Houston, TX, 2015, pp. 1-9.

[18] Y. Borofsky, " Towards a Transdisciplinary Approach to Rural Electrification for Universal Access in India", Massachusetts Institute of Technology, June 2015.

[19] C. Cader, P. Blechinger, P. Bertheau," Electrification Planning with Focus on Hybrid Mini-grids – A Comprehensive Modelling Approach for the Global South", Energy Procedia, Volume 99, 2016, Pages 269-276, ISSN 1876-6102.

[20] F. Kemausuor, E. Adkins, I. Adu-Poku, A. Brew-Hammond, V. Modi, "Electrification planning using Network Planner tool: The case of Ghana", Energy for Sustainable Development, Volume 19, 2014, Pages 92-101, ISSN 0973-0826.

[21] D. Ellman, “The Reference Electrification Model: A Computer Model for Planning Rural Electricity Access”, Massachusetts Institute of Technology, June 2015.

[22] T. Cotterman, et al., “The Reference Electrification Model: A Decision Support Tool to Enable Smart Electricity Access Planning”, TATA Center, Massachusetts Institute of Technology, 2014.

[23] Lambert T., Gilman P., Lilienthal P., “Micropower system modeling with HOMER,” Integration of Alternative Sources of Energy, Farret FA, Simões MG, John Wiley & Sons, December 2005, ISBN 0471712329.

[24] Lilienthal P.D., Lambert T.W., Gilman P., “Computer Modeling of Renewable Power Systems,” Cleveland CJ, editor-in-chief, Encyclopedia of Energy, Elsevier Inc., Volume 1, pp. 633-647, NREL Report No. CH-710-36771, 2004.

[25] X. Cheng, M. Korpås and H. Farahmand, "The impact of electrification on power system in Northern Europe," 2017 14th International Conference on the European Energy Market (EEM), Dresden, 2017, pp. 1-7.

[26] Callavik, M.; Bahrman, M.; Sandeberg, P., "Technology developments and plans to solve operational challenges facilitating the HVDC offshore grid," in Power and Energy Society General Meeting, 2012 IEEE , vol., no., pp.1-6, 22-26 July 2012.

[27] Catmull, S.; Chippendale, R.D.; Pilgrim, J.A.; Hutton, G.; Cangy, P., "Cyclic Load Profiles for Offshore Wind Farm Cable Rating," in Power Delivery, IEEE Transactions on , vol.PP, no.99, pp.1-1.

[28] International Renewable Energy Agency, "Renewable Energy Technologies: Cost Analysis Series."

[29] Padmavathi Lakshmanan, Jun Liang, Nicholas Jenkins, Assessment of collection systems for HVDC connected offshore wind farms, Electric Power Systems Research, Volume 129, December 2015, Pages 75-82, ISSN 0378-7796, http://dx.doi.org/10.1016/j.epsr.2015.07.015.

[30] N. Barberis Negra, J. Todorovic, T. Ackermann, Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms, Electric Power Systems Research, Volume 76, Issue 11, July 2006, Pages 916-927, ISSN 0378-7796.

[31] O. A. Ansari, N. Safari and C. Y. Chung, "Reliability assessment of microgrid with renewable generation and prioritized loads," 2016 IEEE Green Energy and Systems Conference (IGSEC), Long Beach, CA, 2016, pp. 1-6.

[32] S. Sulaeman, M. Benidris, J. Mitra and C. Singh, "A Wind Farm Reliability Model Considering Both Wind Variability and Turbine Forced Outages," in IEEE Transactions on Sustainable Energy, vol. 8, no. 2, pp. 629-637, April 2017.

[33] Samaan, N.A.: 'Reliability assessment of electrical power systems using genetic algorithms'. Doctor of philosophy dissertation, Department of Electrical Engineering, Texas A&M University, 2004.

[34] M. Al-Muhaini, G. T. Heydt, "An algorithm for reliability bounds evaluation for power distribution system", Journal of Engineering Research, Iss. 1, pp. 181-199. 2013.

[35] C. Borges, E. Cantarino, "Microgrids Reliability Evaluation with Renewable Distributed Generation and Storage Systems", IFAC Proceedings Volumes, Vol. 44, Iss. 1, pp. 11695-11700, 2011.

[36] A. Gusmao and M. Groissböck, "Capacity value of photovoltaic and wind power plants in an isolated Mini-grid in the Kingdom of Saudi Arabia," 2015 Saudi Arabia Smart Grid (SASG), Jeddah, 2015, pp. 1-8.

[37] D. C. Yu, T. C. Nguyen and P. Haddawy, "Bayesian network model for reliability assessment of power systems," in IEEE Transactions on Power Systems, vol. 14, no. 2, pp. 426-432, May 1999.

[38] L. Gao, Y. Zhou, C. Li, L. Huo, "Reliability Assessment of Distribution Systems With Distributed Generation Based On Bayesian Networks", Engineering Review, Vol. 34, Issue 1, 55-62, 2014.

[39] M. Eliassi, A. K. Dashtaki, H. Seifi, M. R. Haghifam, C. Singh, "Application of Bayesian Network in Composite Power System Reliability Assessment and Reliability-based Analysis", IET Gener. Transm. Distrib., 2015, Vol. 9, Iss. 13, pp. 1755-1764.

[40] K. U. Leuven, "The Economic Value of VSC HVDC Compared to HVAC for Offshore Wind Farms", Master Thesis, Katholieke Universitiet, 2008.

[41] Lazaros Lazaridis, "Economic Comparison of HVAC and HVDC Solutions for Large Offshore Wind Farms Under Special Consideration of Reliability", Master Thesis, Royal Institute of Technology, 2005.

[42] K. Burges, et al., "Study on the Comparative Merits of Overhead Electricity Transmission Lines Versus Underground Cables", Golder Associates, May 2008.

[43] P. S. Jones and C. C. Davidson, "Calculation of power losses for MMC-based VSC HVDC stations," 2013 15th European Conference on Power Electronics and Applications (EPE), Lille, 2013, pp. 1-10.
[44] "Offshore Grid Initiative. "Offshore Transmission Technology", The Regional Group North Sea For North Seas Countries, European Network of Transmission System Operators for Electricity. ENTSOE. Nov. 2011.
[45] Darrel Locke, "Guide to the Wiring Regulations: 17th Edition IEE Wiring Regulations (BS 7671: 2008)", John Wiley & Sons Ltd. ISBN: 978-0-470-51685-0, 2008] ["BS EN 60228:2005: Conductors of insulated cables", IEC, BSI, March 2005.
[46] "XLPE Submarine Cable Systems Attachment to XLPE Land Cable Sysemts - User's Guide." ABB. Rev 5.
[47] XLPE Submarine Cable Systems: Attachment to XLPE Land Cable Systems- User's Guide ABB Revision 5, 2010-04, 2GM 5007 -sub GB rev5.
[48] HVDC Light ® Cables: Submarine and Land Power Cables ABB, HVC 2GM5001-gb 3000 rev. 2006-04-10.
[49] High Voltage XLPE Cable Systems Technical User Guide, BRUGG Cables, 2006.
[50] J. R. Lluch, "Power Transmission Systems for Offshore Wind Farm: Technical-Economic Analysis", Thesis, Barcelona School of Industrial Engineering. ETSEIB. July 2015.
[51] "Capital Cost Estimation for Utility Scale Electricity Generation Plants" U. S. Energy Information Administration, Washington, DC, Nov. 2016.
[52] "The Bergen marine engine and propulsion portfolio 2017", Rolls Royce, 2017, https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/marine-product-finder/marine-engine-and-propulsion-programme-2017.pdf.
[53] "Global Wind Statistics 2017", Global Wind Energy Council, Feb, 2018.
[54] Petr Sklenicka, Jan Zouhar, "Predicting the visual impact of onshore wind farms via landscape indices: A method for objectivizing planning and decision processes", Applied Energy, Volume 209, 2018, Pages 445-454, ISSN 0306-2619,
[55] "Environmental Impacts of Wind-Energy Projects", National Research Council (NRC), , Washington, DC, The National Academies Press, 2007, https://doi.org/10.17226/11935.
[56] M.S. Ismail, M. Moghavvemi, T.M.I. Mahlia, K.M. Muttaqi, S. Moghavvemi, Effective utilization of excess energy in standalone hybrid renewable energy systems for improving

comfort ability and reducing cost of energy: A review and analysis, Renewable and Sustainable Energy Reviews, Volume 42, 2015, Pages 726-734, ISSN 1364-0321.
[57] S. Georgios. "Techono-Economical Analysis of DC Collection Grid for Offshore Wind Park." Master Thesis. The University of Nottingham. 2010.
[58] S. Lundberg, "Performance Comparison of Wind Park Configurations," 2003.
[59] M. Dicorato, G. Forte, M. Pisani, M. Trovato, Guidelines for assessment of investment cost for offshore wind generation, Renewable Energy, Volume 36, Issue 8, August 2011, Pages 2043-2051, ISSN 0960-1481, http://dx.doi.org/10.1016/j.renene.2011.01.003.
[60] Mark J. Kaiser, Brain F. Snyder, "Offshore Wind Energy Cost Modeling: Installations and Decommissioning", Springer-Verlag London, Ed. 1, 2012 DOI: 10.1007/978-1-4471-2488-7.
[61] "study of the cost of offshore wind generation", Offshore Design Engineering, 2007. http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/files/file38125.pdf.
[62] Website: Natural Gas Prices, US Energy Information Administration .https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm.
[63] D. Koller, N. Friedman, "Probabilistic Graphical Model: Principles and Techniques", The MIT Press, Boston, Untied State, 1 edition, July 31, 2009, ISBN 978-0-262-01319-2.
[64] Ben-Gal I., Bayesian Networks, in Ruggeri F., Faltin F. & Kenett R., Encyclopedia of Statistics in Quality & Reliability, Wiley & Sons (2007).
[65] K. Murphy, "An Introduction to Graphical Models", Rap. Tech, pp. 1-19, May 2001.
[66] R. Billinton et al., "A reliability test system for educational purposes-basic data," in IEEE Transactions on Power Systems, vol. 4, no. 3, pp. 1238-1244, Aug 1989.
[67] Renewable Resource Atlas, King Abdullah City for Atomic and Renewable Energy (K.A.CARE), Saudi Arabia, Online: http://rratlas.energy.gov.sa , 2015.
[68] S. Iain, P. Stefan, "Using Bias-Corrected Reanalysis to Simulate Current and Future Wind Power Output. Energy, 2016, 114, pp. 1224-1239.
[69] M. Avendano-Mora, M. Barnes and J. Y. Chan, "Comparison of control strategies for multiterminal VSC-HVDC systems for offshore wind farm integration," 7th IET International Conference on Power Electronics, Machines and Drives (PEMD 2014), Manchester, 2014, pp. 1-6.
[70] J. H. Mathews, K. D. Fink, "Numerical Method Using MATLAB: Chapter 8 Numerical Optimization", Pearson Prentice Hall, 4th Edition, 2004.

[71] H. Ergun, D. Van Hertem, R. Belmans, "Transmission System Topology Optimization for Large-Scale Offshore Wind Integration", Sustainable Energy IEEE Transactions on, vol. 3, no. 4, pp. 908-917, Oct. 2012.
[72] A. Conn, K. Scheinberg, L. Vicente, “Introduction to Derivative-Free Optimization,” MPS-SIAM Book Series on Optimization, SIAM, Philadelphia, USD, 2009
[73] Godfrey A. Walters & Tilman Lohbeck (2007) “Optimal Layout of Tree Networks Using Genetic Algorithms,” Engineering Optimization, 22:1, 27-48, DOI: 10.1080/03052159308941324
[74] Goldberg. D. E. (1989) Generic Algorithms in Search. Optimization and Machine Learning. Addison-Wesley Publishing Company
[75] F. Herrera, M. Lozano, J. L. Verdegay, “Tackling Real-Coded Genetic Algorithm: Operators and Tools for Behavioral Analysis,” Artificial Intelligence Review, vol. 12, pp. 265 – 319, 1998.
[76] Eshelman, Larry & Schaffer, J. (1992). Real-Coded Genetic Algorithms and Interval-Schema. 2. 10.1016/B978-0-08-094832-4.50018-0.
[77] “Saudi Aramco Commissions Haradh GOSP-3,” Oil and Gas Journal, 2006, Online link: https://www.ogj.com/articles/2006/02/saudi-aramco-commissions-haradh-gosp-3.html, accessed on: April, 2018
[78] V. L. Vachhani, V. K. Dabhi and H. B. Prajapati, "Survey of multi objective evolutionary algorithms," 2015 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2015], Nagercoil, 2015, pp. 1-9.
[79] Iain Staffell, Stefan Pfenninger, “Using bias-corrected reanalysis to simulate current and future wind power output”, Energy, Volume 114, 2016, Pages 1224-1239, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2016.08.068.
[80] “Gamesa G132-5.0MW,” Wind Turbine Models, Link: https://en.wind-turbine-models.com/turbines/768-gamesa-g132-5.0mw, accessed on April 2018.

APPENDIX A

SUBMARINE CABLE SPECIFICATION

Table A.1: Submarine Cable Ampacity and Resistance [45]

Size (Kcmil)	Size (mm^2)	Ampacity (A)	Resistance (Ohm/km)
180	95	300	0.1930
250	120	340	0.1530
300	150	375	0.1240
370	185	420	0.0991
500	240	480	0.0754
600	300	530	0.0601
800	400	590	0.0470
1000	500	655	0.0366
1250	630	715	0.0221
1600	800	745	0.0193
2000	1000	775	0.0176

Table A.2: Submarine Cable Inductance and Capacitance Values [46]

Size **mm2**	**30 kV** **uf/km**	**30 kV** **mH/km**	**45kV** **uF/Km**	**45kV** **mH/Km**	**66KV** **uF/km**	**66KV** **mH/km**	**132kV** **uF/km**	**132kV** **mH/km**	**220kV** **uF/km**	**220kV** **mH/km**
120	0.19	0.42	0.19	0.42	0.18	0.43	-	-	-	-
150	0.21	0.41	0.21	0.40	0.19	0.41	-	-	-	-
185	0.22	0.39	0.22	0.39	0.2	0.4	0.13	0.47	-	-
240	0.24	0.38	0.24	0.37	0.22	0.38	0.14	0.44	-	-
300	0.26	0.36	0.26	0.36	0.24	0.37	0.16	0.42	-	-
400	0.29	0.35	0.29	0.35	0.26	0.35	0.18	0.40	-	-
500	0.32	0.34	0.32	0.33	0.29	0.34	0.20	0.38	0.14	0.43
630	0.35	0.32	0.35	0.32	0.32	0.33	0.21	0.37	0.16	0.41
800	0.38	0.31	0.38	0.32	0.35	0.32	0.23	0.36	0.17	0.40
1000	0.41	0.30	0.42	0.30	0.38	0.31	0.25	0.35	0.19	0.38

VITAE

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Biography

Mohannad is a Research Specialist at the Centre for Complex Engineering Systems at King Abdulaziz City for Science and Technology (KACST) and Massachusetts Institute of Technology (MIT). He received his bachelor degree in electrical engineering from King Fahad University for Petroleum and Minerals (KFUPM) specialized in power systems. Prior to joining KACST, Mohannad worked at Saudi Aramco from 2013 to 2017 in different fields including reliability and operation engineer, facility engineer, project engineer and safety coordinator. His research interest includes power system planning, reliability assessment, and application of artificial intelligence in power systems. In 2015, Mohannad won the best paper award at Saudi Arabia Smart Grid Conference 2015 for his paper about Offshore Wind Energy Planning in Saudi Arabia.

Publications

1. M. Alkhraijah, M. Abido, “Power Quality Classification Using Neuro Fuzzy Logic Inference System”, IEEE-GCC, Bahrain, 2017
2. M. Alkhraijah, I. El-Amin, “Optimization Planning for Large-Scale Offshore Wind Farms using Multi-terminal HVDC Transmission System”, Saudi Arabia Smart Grid Conference, Jeddah, 2015. “Best Paper Award” at the conference
3. M. Alkhraijah, I. El-Amin, “Design Standalone PV System for KFUPM Beach”, Saudi Arabia Smart Grid Conference, Jeddah, 2014