Comparative Technical and Life Cycle Cost Assessment of VSR and STATCOM for Long HVAC Submarine Cables

by

Mufarreh Saad Algahtani

A thesis

presented to the University of Waterloo

in fulfilment of the

thesis requirement for the degree of

Master of Applied Science

in

Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2026

© Mufarreh Saad Algahtani 2026

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

Long HVAC submarine cables generate significant capacitive charging current, which can cause voltage rise, reactive-power imbalance, and operational limitations when supplying offshore loads. Reactive power compensation is then required to maintain acceptable voltage performance and support reliable offshore power transmission. This thesis compares two compensation technologies for a long offshore HVAC submarine cable system: variable shunt reactors (VSRs) and static synchronous compensators (STATCOMs). The study is based on an developed PSCAD model of a double-circuit offshore transmission system supplying a constant PQ load. Three configurations are evaluated: an uncompensated baseline, a VSR-compensated system, and a STATCOM-compensated system. The technical assessment includes steady-state voltage performance, zero-sequence frequency scan behavior, transient recovery voltage, and response to sudden load loss.

The simulation results show that the uncompensated system experiences an unacceptable voltage rise, with the receiving end voltage reaching approximately 1.15 p.u. Both the VSR and STATCOM configurations reduce the voltage profile to within the adopted 0.95–1.05 p.u. operating range under light-load and full-load conditions. The frequency scan results show that compensation technology affects the zero-sequence resonance characteristic, with the STATCOM configuration shifting the dominant impedance peak to a higher frequency than the VSR configuration. The transient recovery voltage results show that both compensation alternatives remain within the specified breaker capability limits for all simulated fault cases. The disturbance response results also show acceptable voltage behavior following sudden load loss.

A Life cycle cost assessment is then performed using a 20-year life-cycle cost method. The results show that the VSR alternative has a significantly lower total life-cycle cost than the STATCOM alternative, with estimated values of approximately $51.04 million and $284.16 million, respectively. Although STATCOM provides faster and more flexible reactive-power control, its higher capital cost, higher active losses, and higher operation and maintenance cost make it less economical for the studied case. Therefore, the VSR configuration is identified as the more cost-

effective solution for this offshore HVAC submarine-cable application, while the STATCOM remains technically feasible but economically less attractive.

Acknowledgements

First and foremost, I would like to praise Allah for helping and guiding me through this work and giving me the patience and health necessary to complete my master's degree. My deepest thanks and appreciation go out to my supervisor, Prof. Ayman El-Hag, for his patience, assistance, guidance, inspiration, support, great supervision, and above all, friendship. Special thanks to my parents, family, and friends for their help and support. I would also like to express my sincere appreciation to Prof. Ramadan El Shatshat for his valuable feedback and guidance during the development of this work. I would also like to extend my sincere thanks to Prof. Sahar Azad for providing me with access to the PSCAD license, which was essential for completing the simulation work in this thesis.

Table of Contents

Author's Declaration ii
Abstract iii
Acknowledgements v
List of figures viii
List of tables x
Chapter 1 Introduction 1
1.1 Background 1
1.2 Problem Statement 1
1.3 Research Objectives 2
1.4 Thesis Organization 2
Chapter 2 Literature Review 3
2.1 Reactive Power Behavior in Long HVAC Submarine Cables 4
2.1.1 Physical Modeling of XLPE Submarine Cable Capacitance 4
2.1.2 Ferranti Effect on Submarine cables 6
2.2 Compensation Placement in Offshore HVAC Systems 10
2.2.1 Terminal Compensation Placement: Onshore, Offshore, and intermediate Schemes 11
2.2.2 Reactive Power Compensation Methods: Capabilities and Limitations 14
2.3 VSR and STATCOM Compensation for Long HVAC Submarine Links 17
2.3.1 Variable Shunt Reactor Applications 18
2.3.2 STATCOM Applications 22
2.4 Identified Research Gap 25
Chapter 3 Methodology and System Modeling 27
3.1 Research Framework and System Description 27
3.2 Component and Simulation Modeling 31
3.3 Comparative Assessment Method 32
Chapter 4 Technical Results and Discussion 34
4.1 Steady State Voltage Performance 34
4.2 Zero Sequence Frequency Scan Results 41

4.3 Transient Recovery Voltage Performance 45
4.4 Disturbance and Tap Change Response 53
4.5 Summary of Technical Findings 56
Chapter 5 life Cycle Cost Assessment 57
5.1 Life Cycle Cost Method 57
5.2 Cost Assumptions 58
5.3 Capital Cost Comparison 59
5.4 Energy Loss and Maintenance Cost 60
5.5 Total Life Cycle Cost Comparison 61
5.6 Discussion 61
Chapter 6 Conclusions and Future Work 63
Bibliography 65

List of figures

Figure 1: VSR schematic model from PSCAD model 19
Figure 2: STATCOM schematic from the PSCAD model..... 22
Figure 3: Simplified single line diagrams of the 230 kV offshore HVAC system studied: (a) VSR compensation configuration and (b) STATCOM compensation configuration. 29
Figure 4: Uncompensated voltage response at the onshore and offshore terminals. 34
Figure 5: Uncompensated voltage profile along the submarine cable. 35
Figure 6: Uncompensated current profile along the submarine cable. 35
Figure 7: Steady state voltage response with VSR compensation at 10% loading. 36
Figure 8: Voltage profile along the submarine cable with VSR compensation at 10% loading. .. 37
Figure 9: Steady state voltage response with VSR compensation at 100% loading. 37
Figure 10: Voltage profile along the submarine cable with VSR compensation at 100% loading. 38
Figure 11: Steady state voltage response with STATCOM compensation at 10% loading. 39
Figure 12: Voltage profile along the submarine cable with STATCOM compensation at 10% loading. 39
Figure 13: Steady state voltage response with STATCOM compensation at 100% loading. 40
Figure 14: Voltage profile along the submarine cable with STATCOM compensation at 100% loading. 40
Figure 15: Zero sequence frequency scan comparison at 10% loading at onshore bus. 42
Figure 16: Zero sequence frequency scan comparison at 10% loading at offshore bus. 42
Figure 17: Zero sequence frequency scan comparison at 100% loading at onshore bus. 43
Figure 18: Zero sequence frequency scan comparison at 100% loading at offshore bus. 44
Figure 19: VSR TRV response for offshore 3ph fault at 10% loading. 46
Figure 20: VSR TRV response for offshore SLG fault at 10% loading. 46
Figure 21: VSR TRV response for offshore LLG fault at 10% loading. 46
Figure 22: VSR TRV response for offshore LL fault at 10% loading. 47
Figure 23: VSR TRV response for offshore 3ph fault at 100% loading. 47
Figure 24: VSR TRV response for offshore SLG fault at 100% loading. 48
Figure 25: VSR TRV response for offshore LLG fault at 100% loading. 48
Figure 26: VSR TRV response for offshore LL fault at 100% loading. 48
Figure 27: STATCOM TRV response for offshore 3ph fault at 10% loading. 49
Figure 28: STATCOM TRV response for offshore SLG fault at 10% loading. 50
Figure 29: STATCOM TRV response for offshore LLG fault at 10% loading. 50
Figure 30: STATCOM TRV response for offshore LL fault at 10% loading. 50
Figure 31: STATCOM TRV response for offshore 3ph fault at 100% loading. 51
Figure 32: STATCOM TRV response for offshore SLG fault at 100% loading. 51
Figure 33: STATCOM TRV response for offshore LLG fault at 100% loading. 52

Figure 34: STATCOM TRV response for offshore LL fault at 100% loading. 52
Figure 35: VSR voltage response during tap change operation and sudden 20 MVA load loss... 54
Figure 36: STATCOM voltage response during sudden 20 MVA load loss. 55

List of tables

Table 1: Summary of reactive power compensation methods for long HVAC submarine cables [3], [8] [10] [12] 17
Table 2: Comparative characteristics of VSR and STATCOM compensation for long HVAC submarine cables [3], [8] [4] [12] 24
Table 3: Principal parameters of the studied offshore HVAC system 28
Table 4: Compensation configurations considered in the comparative study 30
Table 5: Electrical parameters of the principal submarine cable sections 31
Table 6: Steady state voltage comparison 41
Table 7: Zero sequence frequency scan comparison 44
Table 8: VSR TRV results 49
Table 9: STATCOM TRV results 52
Table 10: Main economic assumptions 58
Table 11: Capital cost comparison 59
Table 12: Present value of operating costs 60
Table 13: Total 20-year life cycle cost comparison 61

Chapter 1
Introduction

1.1 Background

Offshore industrial facilities require reliable electrical power systems to operate large process loads, auxiliary systems, and supporting infrastructure. For offshore loads, HVAC submarine cables are used to transfer power from an onshore grid or substation to the offshore facility. This approach can be technically practical and operationally familiar, but the electrical behavior of long submarine cables is different from that of overhead transmission lines.

A major challenge in long HVAC submarine cables is their high capacitance. Cable shunt capacitance produces charging current and reactive power, especially when the connected load is low. This will lead to voltage rise along the cable, increased reactive power circulation, and difficult voltage control. As a result, reactive power compensation becomes an essential part of the design and operation of offshore HVAC transmission systems.

1.2 Problem Statement

Reactive power compensation for offshore HVAC submarine cables can be done using different technologies. Variable shunt reactors (VSR) are commonly used because they absorb cable charging reactive power and can adjust their compensation level through tap changing operation. Static synchronous compensators (STATCOMs) provide faster and more flexible dynamic reactive power control using power-electronic converters. However, the technically optimum option is not always the most economical one. Therefore, an adequate comparison must consider both technical performance and life-cycle cost.

This thesis addresses this issue by comparing VSR and STATCOM compensation for a long HVAC submarine-cable system supplying an offshore constant PQ industrial load. The comparison considers voltage performance, resonance behavior, transient recovery voltage, disturbance response, and total life cycle cost.

1.3 Research Objectives

The main objective of this thesis is to compare the technical and economic performance of VSR and STATCOM compensation for an offshore HVAC submarine cable system under the same operating conditions.

The specific objectives are:

- To model the studied offshore HVAC submarine cable system in PSCAD using the industrial system configuration.
- To evaluate the voltage behavior of the uncompensated, VSR compensated, and STATCOM compensated systems.
- To compare the resonance, transient recovery voltage, and disturbance response performance of the VSR and STATCOM.
- To estimate and compare the life-cycle cost of the two compensation technologies.
- To identify the more suitable compensation solution for the studied offshore HVAC application based on combined technical and economic performance.

1.4 Thesis Organization

Chapter 2 reviews the relevant literature on reactive power behavior in long HVAC submarine cables, compensation placement, and VSR and STATCOM applications. Chapter 3 will be presenting the research framework, system description, component models, and comparative assessment method. Chapter 4 will discuss the technical simulation results, including steady state voltage performance, frequency scan results, transient recovery voltage, and disturbance response. Chapter 5 will present the life cycle cost assessment of the VSR and STATCOM systems. Chapter 6 summarizes the main conclusions and identifies areas for future work.

Chapter 2
Literature Review

Long HVAC submarine cables are the main way used to connect offshore generation, interconnect power systems, and supply remote offshore facilities where overhead transmission is not feasible. Their electrical behavior differs substantially from overhead lines because the compact cable geometry produces high shunt capacitance which will result in high charging current and capacitive reactive power generation as cable length increases. These characteristics reduce the active power transfer capability available within the cable ampacity limit and complicated voltage regulation, particularly under no load and light load conditions where the Ferranti effect can produce high receiving end voltage. Reactive power compensation is becoming an essential design requirement for long HVAC submarine cables, and the selected compensation equipment must consider not only the required MVAr rating but also device location, cable current distribution, voltage profile, switching performance, and practical offshore installation constraints.

A range of passive and active compensation technologies can be used to address these challenges. Fixed shunt reactors provide a mature and relatively simple means of absorbing cable generated reactive power, while VSRs extend this concept by allowing the compensation level to be adjusted through controlled changes in reactor inductance. Converter based devices such as STATCOMs provide a continuous and faster reactive power control and can contribute to dynamic voltage regulation and system stability. However, these benefits are accompanied by greater converter complexity, higher capital cost, and additional auxiliary systems. The suitability of each technology therefore depends on the electrical characteristics of the system under study and on whether the main requirement is steady state compensation or rapid dynamic support. This distinction is particularly important for long HVAC links supplying offshore industrial facilities, where the receiving demand may be represented by relatively stable constant PQ loads rather than the variable operating conditions commonly associated with offshore wind generation.

Accordingly, this chapter first examines the physical origin of reactive power behavior in cross linked polyethylene (XLPE) submarine cables and the resulting Ferranti effect in long HVAC links.

It then reviews compensation placement, including terminal, double-ended, and intermediate arrangements, before assessing the capabilities and limitations of the principal compensation methods. A detailed review is then given to VSR and STATCOM technologies because they represent the two controllable compensation alternatives evaluated in this thesis. The chapter concludes by identifying limitations in existing literature, particularly the limited direct life cycle cost comparison of VSR and STATCOM solutions under the same system and load assumptions. These gaps provide the motivation for the comparative technical and life cycle cost assessment developed in the remainder of this thesis.

2.1 Reactive Power Behavior in Long HVAC Submarine Cables

Long HVAC submarine cables exhibit reactive power behavior that differs significantly from overhead transmission lines because of their high shunt capacitance and distributed electrical parameters. The compact conductor insulation screen geometry of XLPE submarine cables produces substantial charging current, which increases with cable length and remains present when active power transfer is low. As the cable becomes longer, this capacitive behavior affects both its current carrying capability and its voltage profile, particularly under no load and light load conditions, where receiving end or internal overvoltage may develop through the Ferranti effect. A clear understanding of these phenomena is therefore necessary before compensation requirements can be assessed. Accordingly, this section first examines the physical basis of XLPE cable capacitance and then evaluates how the resulting charging current influences voltage rise and reactive power flow in long offshore HVAC links.

2.1.1 Physical Modeling of XLPE Submarine Cable Capacitance

The high shunt capacitance of HVAC submarine cables is a result of their compact structure and the dielectric properties of their insulation system. Unlike overhead lines, where the bare conductors are separated by large distances of air, submarine cable conductors are placed inside an insulated structure and surrounded by conductive screens and a metallic sheath [1]. This arrangement will create a much stronger electric field coupling between the conductor and the grounded surrounding layers than the electric field in overhead transmission lines [1]. In modern submarine XLPE cable designs is the standard insulation material, and the cable insulation system

typically includes an inner conducting screen, the insulation layer, and an outer semiconducting screen [2]. Because of this structure extends continuously along the cable, it behaves as a distributed capacitor, causing the total capacitance to become significant over long transmission distances [1].

The dielectric behavior of XLPE insulation is central to this physical model and modern submarine cables since it provides electrical insulation and improved thermal stability under various operating conditions. As stated in the CIGRE report 490, “The cross linking of polyethylene (in particular low-density polyethylene, LDPE) is an irreversible process (i. e. no re melting is possible) to form a three-dimensional network that makes the insulation more thermally stable” [2]. In addition, the semiconducting inner and outer screens contain carbon black and are designed to control the electric field and support reliable high voltage performance [2]. This means that the electrical behavior of the cable is not determined by XLPE alone, but by the full insulation system formed by the conductor, the screens, the insulation and the sheath. Comparing this to overhead lines, where the air acts as the main dielectric medium and conductor spacing is much larger, this layered cable construction naturally leads to much higher capacitance per unit length.

For a submarine cable, the capacitance can be represented by this formula.

$$C = \frac{2\pi\epsilon_0\epsilon_r}{\ln(D/d)} \qquad 1$$

where ϵ_0 is the permittivity, ϵ_r is the relative permittivity of the insulation, d is the conductor diameter, and D is the effective inner diameter at the grounded screen or sheath boundary.

This formula shows that capacitance increases when the dielectric permittivity is higher and when the radial spacing between the conductor and the grounded sheath is smaller. Both conditions are present in XLPE submarine cables. The compact cable geometry, characterized by short internal electrical distances and a solid dielectric medium, results in a high shunt capacitance compared with overhead transmission lines. For the 1000 mm² cable considered in this study, the outer diameter is 239 mm, further illustrating its compact construction.

This high capacitance is directly connected to the charging current problem in long HVAC submarine cables. The cable shunt branch is represented by the admittance $Y = G + j\omega C$, where C is the shunt capacitance [1]. As the cable length increases, the total capacitance increases proportionally, and the charging current rises with operating voltage and frequency. Therefore, even when the receiving end load is light, a long submarine cable can draw and generate substantial reactive current and the cable will act as a load. This is the physical basis for voltage rise phenomena in lightly loaded submarine cables and explains why reactive power management becomes a major design issue in offshore HVAC transmission.

2.1.2 Ferranti Effect on Submarine cables

The high shunt capacitance discussed in the previous section has a direct influence on the voltage profile of long HVAC submarine cables. When the cable is energized under no load or light load conditions, the active current supplied to the receiving end load is small, but the distributed cable capacitance continues to draw charging current [3]. This capacitive current interacts with the series inductance of the cable and the upstream network, causing the voltage toward the receiving end to increase above the sending end value [3], [4]. This phenomenon is known as the Ferranti effect and represents an important steady state limitation in long HVAC cable systems, particularly during cable energization, low load operation, and sudden load rejection [5]. Recent studies of subsea HVAC connections also show that the voltage profile can change between light load and heavy load conditions, which makes voltage regulation increasingly difficult as cable length increases with different loading conditions [6].

The physical origin of the Ferranti effect can first be related to the cable charging current. For a cable with capacitance per unit length (C') and total length (l), the total capacitance increases approximately in proportion to cable length [4]. The approximate charging current can therefore be expressed as:

$$\boldsymbol{I_c \approx \omega C' \ell V} \qquad \mathbf{2}$$

where ($\boldsymbol{I_c}$) is the charging current, ($\boldsymbol{\omega = 2\pi f}$) is the angular frequency, ($\boldsymbol{C'}$) is the cable capacitance per unit length, ($\boldsymbol{\ell}$) is the cable length, and ($\boldsymbol{V}$) is the relevant phase voltage [5]. The corresponding capacitive reactive power can be written in per phase form as:

$$[\boldsymbol{Q_c, ph} \approx \boldsymbol{\omega C'\ell V^2}] \quad \mathbf{3}$$

For a balanced three phase cable system, the total reactive power is:

$$\boldsymbol{Q_c} \approx \boldsymbol{3\omega C'\ell V^2} \quad \mathbf{4}$$

These relationships show that the reactive power generated by the cable increases with cable length and with the square of the operating voltage. Consequently, long high voltage submarine cables can produce substantial capacitive reactive power especially when the offshore active power demand is very small.

For long submarine cables, the Ferranti effect is more accurately represented using a distributed parameter transmission line model rather than a single lumped capacitance [3]. The relationship between the sending end and receiving end quantities can be expressed using the transmission line matrix:

$$\begin{bmatrix} \boldsymbol{V_S} \\ \boldsymbol{I_S} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\cos h(\gamma\ell)} & \boldsymbol{Z_c \sin h(\gamma\ell)} \\ \boldsymbol{\left(\frac{1}{Z_c}\right) \sin h(\gamma\ell)} & \boldsymbol{\cos h(\gamma\ell)} \end{bmatrix} \begin{bmatrix} \boldsymbol{V_R} \\ \boldsymbol{I_R} \end{bmatrix} \quad \mathbf{5}$$

where (V_S) and (I_S) are the sending end voltage and current, (V_R) and (I_R) are the receiving end quantities, ($\boldsymbol{\gamma}$) is the propagation constant, (Z_c) is the characteristic impedance, and ($\boldsymbol{\ell}$) is the cable length. This representation is important because voltage and current vary continuously along a long cable. Therefore, examining only the sending end and receiving end buses may not be sufficient to identify the maximum voltage experienced by the cable insulation [3].

Under no load conditions, the receiving end current is approximately zero:

$$\boldsymbol{I_R = 0} \quad \mathbf{6}$$

The long line voltage relationship therefore reduces to:

$$[\boldsymbol{V_S = V_R cosh(\gamma \ell)}] \quad \textbf{7}$$

Rearranging the expression gives the receiving end voltage:

$$\left[\boldsymbol{V_R = \frac{V_S}{cosh(\gamma \ell)}}\right] \quad \textbf{8}$$

For a low loss cable, the propagation constant can be approximated as:

$$\boldsymbol{\gamma \approx j\beta} \quad \textbf{9}$$

where the phase constant is approximately:

$$\boldsymbol{\beta \approx \omega \sqrt{L'C'}} \quad \textbf{10}$$

and (L') and (C') represent the cable inductance and capacitance per unit length. Using the identity:

$$[\boldsymbol{cosh(j\beta \ell) = cos(\beta \ell)}] \quad \textbf{11}$$

the no load receiving end voltage can be approximated as:

$$\left[\boldsymbol{V_R \approx \frac{V_S}{cos(\beta \ell)}}\right] \quad \textbf{12}$$

This expression explains the Ferranti effect analytically. As the length of the cable increases, the value of ($cos(\beta \ell)$) becomes smaller than unity over the relevant operating range, and the receiving end voltage becomes greater than the sending end voltage. The result also shows that the voltage rise is directly influenced by cable length, operating frequency, inductance, and capacitance.

A closely related analytical expression has been developed specifically for subsea HVAC transmission systems [4]. The no load receiving end voltage is represented as:

$$\left\{V_R = \frac{V_S}{cos\left[l\omega\sqrt{L'C'}\right]}\right\} \quad \textbf{13}$$

This equation provides a direct connection between the physical cable parameters discussed in Section 2.1.1 and the system level voltage rise problem. The cable capacitance (C') increases as the length of the transmission link and as a result this strengthens the no load voltage rise effect [4]. Under 0% load the receiving end voltage increases progressively with distance, whereas higher loading reduces the voltage because the load related voltage drop becomes more significant.

The influence of loading conditions is particularly important in offshore systems. Under no load or light load operation, the capacitive charging effect is huge because the receiving end load current is small. As the active power demand increases, the cable also carries additional load current, and the voltage drop across the series impedance becomes more significant. The resulting voltage profile can therefore be substantially different at light and heavy load. A recent review of long HVAC subsea cable connections presents separate voltage and current profiles for light load and heavy load conditions and demonstrates that compensation requirements vary with operating point [6]. This behavior is directly relevant to offshore constant PQ loads because a reduction in demanded active and reactive power can move the system toward a more severe Ferranti operating condition while the cable remains fully energized.

Practical offshore studies confirm that the Ferranti effect is an important engineering constraint rather than only a theoretical long line phenomenon. In a 230 kV offshore HVAC system, no load, light load, and load rejection conditions were identified as critical operating states for receiving end voltage rise [5]. For the uncompensated cable system, the medium line analysis produced

approximately a 4.2% increase in receiving end voltage under no load conditions [5]. The same study calculated approximately 312 Mvar of reactive power generated by the submarine cable and estimated that about 152 Mvar of inductive compensation would be required at the receiving end to maintain the voltage near 1.0 p.u. under the stated assumptions [5]. These results provide

direct evidence that long submarine cables can require large amounts of reactive power absorption even before substantial offshore active power is transferred.

The location of the maximum voltage is also important. The highest voltage does not necessarily occur exactly at the receiving end terminal, particularly when reactors are installed at one or both cable ends [5], [6]. A practical 230 kV offshore study presented a no load voltage profile along the full onshore to offshore transmission path and the results showed that the voltage can reach a maximum voltage within the cable route [5]. CIGRE Technical Brochure 680 similarly notes that terminal compensation may not be sufficient to prevent excessive voltages from developing at intermediate locations along a long cable [3]. Therefore, voltage versus distance analysis is more appropriate than considering only terminal voltage regulation.

The importance of compensation increases further as transmission distance becomes very long. Studies on 420 kV EHVAC offshore wind connections show that reactive power profiles must be controlled to maintain acceptable transmission capability [7]. For progressively longer AC cables, additional intermediate shunt compensation stations were introduced to divide the cable into electrically shorter manageable sections [7]. The study considered transmission distances extending from approximately 90–100 km base cases to several hundred kilometers with increasing numbers of intermediate compensation stations [7]. This demonstrates that cable generated reactive power and voltage regulation become structural design constraints as HVAC distance increases. Moreover, intermediate offshore compensation also requires platforms, equipment, installation, and maintenance which will create the need of economic study of the offshore transmission system.

2.2 Compensation Placement in Offshore HVAC Systems

The reactive power behavior of long HVAC submarine cables, discussed in the previous section, makes reactive power compensation a fundamental consideration in the design of offshore HVAC transmission systems. However, effective compensation depends not only on the required MVAr rating but also on where the compensating equipment should be installed and which technology should be selected. Because cable charging current is distributed continuously along the route,

onshore, offshore, double ended, and intermediate compensation arrangements will show different voltage and current profiles and are subject to different practical constraints. At the same time, available technologies range from mature fixed shunt reactors to adjustable VSRs and faster power electronic devices such as SVCs and STATCOMs and each technology offering different levels of controllability, response speed, complexity, and cost. Accordingly, this section first reviews the influence of compensation placement on long submarine cables and then compares the principal compensation methods in terms of their capabilities and limitations.

2.2.1 Terminal Compensation Placement: Onshore, Offshore, and intermediate Schemes

The location of reactive power compensation is an important design element in long HVAC submarine cables because it affects the voltage profile, reactive power flow, cable current distribution, and offshore equipment requirements. Shunt reactors may be connected at the onshore terminal, the offshore terminal, or at both ends of the cable. Those arrangements are not electrically equivalent because the cable generates charging current continuously along its length. Therefore, a reactor installed at one terminal mainly changes the reactive power balance and current distribution seen from that location, while the remaining cable sections continue to contribute capacitive charging current. The selection of compensation location must consequently consider both terminal voltage regulation and the internal current profile of the whole submarine cable.

Onshore compensation is generally desirable because large reactors can be installed in an accessible substation without consuming limited offshore platform spaces [3], [8]. This practical constraint is especially important for offshore oil and gas facilities, where platform area and equipment weight are restricted [5]. CIGRE Technical Brochure 680 indicates that, where practical, compensation equipment for offshore connections is often installed onshore because offshore platform space is limited and highly valuable [3]. However, onshore placement alone does not necessarily provide the best electrical performance for every cable system. Simulation results for long submarine cables show that changing the compensation applied at the sending

end modifies the current distribution along the complete cable and increasing sending end compensation can reduce current toward the receiving end while increasing current at the sending terminal [3]. The reactor location and rating must therefore be coordinated with the cable ampacity rather than determined solely by the total reactive power generated by the cable [3].

Offshore, or receiving-end, compensation provides more direct control of the remote bus voltage, which is particularly beneficial when the Ferranti effect causes the voltage at the offshore terminal to exceed acceptable limits [5]. A practical 230 kV offshore oil and gas study calculated that approximately 152 Mvar of receiving end compensation would be required to maintain the remote voltage near 1.0 p.u. under the stated no load assumptions [5]. even though, a standard 123 Mvar unit was selected because of physical space and weight limitations on the offshore platform, demonstrating that the electrically preferred reactor rating may not be physically feasible [5]. The remaining compensation duty was therefore shared with an identical onshore reactor and an additional onshore bus connected reactor [5]. This case is particularly relevant to offshore constant load applications because it shows that compensation placement is determined jointly by voltage control, reactive power flow, and practical platform constraints rather than by a single electrical criterion.

Double ended compensation can provide a more balanced arrangement when the cable is sufficiently long or when voltage and current limits cannot be satisfied by a single terminal device. In a 230 kV offshore case, reactors were placed at both the onshore and offshore cable ends, while an additional bus connected reactor managed the remaining reactive power surplus [5]. The study reports that splitting the line connected compensation between both ends supports more consistent cable loading, regulates the offshore voltage, reduces reactive power exported toward the onshore grid, and limits adverse switching effects associated with concentrating large inductive compensation at one location [5].

The choice of location must also consider switching performance and circuit breaker capability. In a 220 kV industrial subsea system, a 62 km cable produced approximately 316 A of charging

current, exceeding the 250 A capacitive interruption limit considered for the circuit breaker in that study [3]. Rigidly connecting the compensation reactor at the cable sending end reduced the residual current that the circuit breaker had to interrupt. However, locating the entire 60 MVAr compensation at that point resulted in a delayed current zero crossing during energization [8]. The final arrangement divided the compensation into two 30 Mvar reactors, with one rigidly connected at the cable sending end and the second connected at the supplying GIS substation, which removed the simulated zero crossing missing condition [8]. This example demonstrates that the preferred location may be governed by switching duties as well as steady state voltage and reactive power requirements.

Overall, the reviewed evidence does not support a universal preference for onshore, offshore, or double ended compensation. Onshore placement reduces offshore installation burden and can control reactive power exchange with the grid, whereas offshore placement provides stronger direct control of the receiving end voltage but is constrained by platform space, weight, accessibility, and maintenance requirements. Double ended schemes can improve the distribution of voltage and current along long cables, but they increase equipment count and system complexity. Furthermore, detailed cable studies show that compensation placement changes the current distribution and may shift the location of the maximum current between the sending and receiving ends [9]. The compensation location should therefore be selected through coordinated load flow, thermal, contingency, and switching studies rather than by compensating a fixed percentage of cable reactive power alone.

For very long HVAC submarine cables, terminal compensation may become insufficient because controlling only the sending and receiving end buses does not necessarily maintain acceptable voltage and current conditions along the complete cable route. CIGRE Technical Brochure 680 notes that, even when compensation is installed at both ends of the cable, excessive voltages may still develop at intermediate locations, particularly under light-load conditions [3]. Intermediate compensation addresses this limitation by absorbing reactive power at an internal location and dividing the long link into electrically shorter sections [7]. Simulation results for long submarine cables further show that compensation applied at an intermediate point can

substantially reduce current in the downstream cable section, although it does not change the upstream current profile before the compensation location [9]. The effect therefore depends on both the compensation rating and its position along the route. Studies evaluating compensation locations at one-third, one-half, and two-thirds of the cable length show that intermediate compensation changes the location at which current relief occurs and can help alleviate cable ampacity constraints [9]. For very long cables, this approach can increase active power transfer capability beyond what is achievable using terminal compensation alone.

The main disadvantage is that the electrically preferred compensation point is often located offshore, where implementation becomes technically and economically difficult. Intermediate shunt compensation may require a dedicated offshore platform with high voltage switchgear, reactors, protection and control systems, auxiliary supplies, and access provisions for inspection and maintenance. These requirements add capital cost, increase system complexity, and introduce additional offshore equipment whose failure may reduce transmission availability and reliability. The engineering challenge is therefore not simply to identify the midpoint of the cable, but to determine whether the improvement in voltage profile, current distribution, and feasible transmission distance justifies the additional offshore infrastructure. This tradeoff is demonstrated in very long distance EHVAC studies, where progressively longer cables require additional intermediate compensation stations, while practical reviews also identify offshore space, construction, and maintenance requirements as major constraints on distributed compensation.

2.2.2 Reactive Power Compensation Methods: Capabilities and Limitations

Fixed shunt reactors remain the conventional solution for absorbing the capacitive reactive power generated by long HVAC cable systems because they are technically mature, relatively simple, and suitable for large bulk compensation duties [3]. Their main advantage is the ability to provide the required reactive power without the converter and control equipment's required by active compensation devices. However, a fixed reactor cannot continuously adapt its output to

changes in loading or operating voltage, and additional switching equipment may be required when several compensation steps are needed [10]. Switching performance must also be considered when a large reactor is directly associated with the cable. In the 220 kV industrial subsea system studied, the 62 km cable produced approximately 316 A of charging current, while concentrating on the required 60 Mvar compensation at one cable end resulted in delayed current zeros during energization [8]. The final design divided the compensation duty between two 30 Mvar reactors, showing that a simple fixed reactor solution may be constrained by circuit breaker capability and electromagnetic switching behavior as well as by steady state reactive power requirements [8].

Variable shunt reactors extend the passive compensation concept by allowing the absorbed reactive power to be adjusted through discrete changes in reactor inductance. This improves operating flexibility when the required compensation changes with cable voltage or loading condition [10]. Practical offshore studies have used VSRs to regulate long HVAC links across different operating states, demonstrating their suitability for large steady state and quasi steady state compensation duties [5]. Nevertheless, VSR control remains limited by the physical tap changing mechanism. The VSR adjustment process occurs step by step, with response determined by the tap changer operating time, generally on the order of several seconds [10]. Because the available reactive power output is discrete rather than continuous, frequent changes in the operating command may also increase tap operations and affect maintenance requirements and equipment lifetime. VSRs therefore provide greater flexibility than fixed reactors but remain less suitable for rapid voltage disturbances than power electronic compensation devices.

Power electronic compensation devices provide a faster and more continuous alternative. SVCs are mature devices that regulate voltage through controllable reactive power exchange, although their implementation may require harmonic filtering and additional substation space [3]. STATCOMs provide continuous and dynamic voltage support with faster response and lower harmonic distortion than conventional SVCs. CIGRE Technical Brochure 680 also identifies their smaller footprint, relative to a comparably rated SVC, as an additional advantage [3]. Their main

limitation is the higher cost and greater power electronic and control complexity associated with converter-based compensation [3]. Some other offshore integration practices use a combination of fixed or variable reactors, STATCOMs, and available inverter reactive power capability according to the required voltage control function [11]. This distinction is important for long HVAC cables because a large part of the charging MVAr is predictable, whereas only part of the compensation duty may require fast dynamic correction which could justify hybrid compensation.

Hybrid compensation seeks to separate these functions by combining a large bulk compensation device with a faster electronically controlled source. A coordinated scheme used a VSR to compensate for the cable reactive power while the inverter-based wind power plant supplied the remaining reactive power difference with fast and continuous control [10]. The VSR tap position was changed only when the fast inverter-based capability approached its operating limit, reducing unnecessary tap operations while maintaining accurate reactive power control at the point of connection [10]. Although the fast source in that study was the wind plant inverter rather than a dedicated STATCOM, but the same principle provides a basis for hybrid VSR–STATCOM architectures. The VSR can absorb the majority of the steady-state capacitive reactive power, while the STATCOM can be dedicated to rapid voltage regulation and fine reactive power control. Such an arrangement can improve operational flexibility, but it introduces additional equipment, protection requirements, and control coordination, so its benefit must be assessed against the added system cost and complexity.

Table 1 shows that no single compensation method is superior under all operating requirements. Fixed reactors provide the simplest solution for predictable bulk reactive power absorption but offer little adaptability, whereas VSRs improve steady state flexibility at the cost of slower and discrete control. SVCs and STATCOMs provide substantially faster regulation, but this capability is accompanied by greater equipment and control complexity, with STATCOMs also carrying a higher cost than passive reactor-based solutions [3]. Hybrid schemes occupy an intermediate position by assigning the dominant cable charging duty to a reactor-based device and reserving faster electronic control for the remaining corrective requirement [10].

Table 1: Summary of reactive power compensation methods for long HVAC submarine cables [3], [8] [10] [12]

Compensation method	Control characteristic	Main advantages	Main limitations	Most suitable role
Fixed shunt reactor	Fixed output	Mature technology, simple architecture, effective for large bulk MVAr absorption	Limited adaptation to changing operating conditions, excessive connected compensation may contribute to switching issue	Base compensation where cable charging demand is predictable
Variable shunt reactor (VSR)	Discrete tap-based adjustment	Adjustable bulk compensation, improved steady state voltage regulation, wider operating range than fixed reactors	Slower response, discrete output, tap wear and maintenance, limited capability for fast disturbances	Steady state regulation
SVC	Continuous thyristor controlled reactive power regulation	Mature dynamic compensation, faster voltage control than mechanically controlled reactors	Harmonic generation and filter need, comparatively large installation footprint	Dynamic voltage regulation where converter level response is required
STATCOM	Continuous converter-based control	Fast response, reactive power absorption and injection, strong dynamic voltage support, relatively compact active compensation solution	Higher cost, converter and control complexity, additional auxiliary and protection requirements	Fast voltage correction and disturbance support
Hybrid compensation	Coordinated bulk and fast compensation	Separates steady state and dynamic duties, improves flexibility, can reduce dependence on continuous tap changing or full active compensation	More equipment, coordination and protection complexity, higher system integration effort	Long links requiring both substantial bulk absorption and fast corrective control

2.3 VSR and STATCOM Compensation for Long HVAC Submarine Links

Following the broader review of reactive-power compensation methods in Section 2.2, this section focuses on VSR and STATCOM technologies because they represent two fundamentally different approaches to controllable compensation in long HVAC submarine links. VSRs provide adjustable inductive reactive-power absorption through discrete tap changes and are therefore primarily suited to large steady-state and slowly varying compensation duties, whereas STATCOMs use power-electronic conversion to provide continuous and faster reactive-power control. This distinction is important because long submarine cables impose persistent charging-power requirements while some offshore systems may also require rapid voltage regulation,

disturbance support, or improved stability under weak-grid conditions. Neither technology is universally preferable; rather, its suitability depends on the required compensation range, response speed, voltage regulation objectives, losses, implementation complexity, and cost. Accordingly, the following subsections examine the operating characteristics, practical applications, and limitations of VSR and STATCOM technologies before comparing their suitability for long HVAC submarine cables supplying offshore loads.

2.3.1 Variable Shunt Reactor Applications

Variable shunt reactor (VSR) provides adjustable inductive compensation by changing the effective reactor inductance rather than operating at a single fixed MVAr rating. In practical designs, this variation is achieved through a regulating winding and an on-load tap changer (OLTC), which changes the effective number of connected turns and therefore the reactor inductance [10]. Figure 1 shows the schematic diagram of VSR model that used in PSCAD.

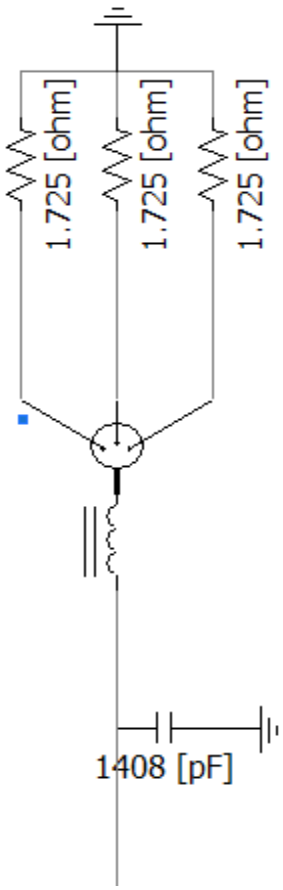


Figure 1: VSR schematic model from PSCAD model

The basic operating principle can be expressed using simplified formula:

$$\left[Q_1 = \frac{V^2}{X_1} = \frac{V^2}{(\omega L)}\right] \quad \mathbf{14}$$

where (ωL) is the reactor reactance, L is the effective inductance, ω is the angular frequency, and V is the RMS voltage across the reactor branch. For a given operating voltage, reducing the effective inductance increases the absorbed inductive reactive power, whereas increasing the inductance reduces it. The tap changer therefore will allow one reactor to cover a range of compensation levels that would otherwise require several fixed reactors. This adjustment occurs in discrete steps, where changes in the effective winding turns produce corresponding changes

in reactive power absorption, making the VSR well suited for fine adjustment of system voltage and cable reactive power balance [10].

The available regulation range and number of tap positions depend on the reactor design and application. The VSR usually varies between approximately half and full rated reactive power, with adjustment determined by tap operation philosophy. In the 230 kV offshore system examined in this paper, the 123 Mvar reactors provide a 40–100% compensation range; the onshore units use 33 tap positions, while the offshore units use 25 [5] & [13]. Another 420 kV VSR provides 80–150 Mvar over 29 tap positions, demonstrating that both range and control resolution are design specific [14]. These examples show that a VSR should not be treated as a continuously variable source. Its output moves between discrete operating points, and the achievable regulation accuracy depends on the MVAr change associated with each tap and for a specific location requirement.

This adjustable characteristic is particularly relevant to long HVAC submarine cables because the required inductive compensation changes with voltage, loading condition, network configuration, and equipment availability. The large charging current generated by a long cable may require strong inductive absorption during no load or light load operation, whereas the optimum compensation level can be lower when the system is in a full load operating condition offshore. VSRs can therefore regulate the voltage profile while also influencing cable current distribution and usable ampacity. In an offshore case, the line connected reactors were divided between the onshore and offshore cable ends and provided a 40–100% controllable range. Under no load operation, the reactors were tapped toward maximum compensation to limit the voltage rise, however under full load conditions the taps were moved to the minimum taps. One evaluated case used approximately 40% onshore and 50% offshore tapping while maintaining the voltage with 0.95 and 1.05 per unit and the cable current below its limiting ampacity [5]. This ability to adapt to different operating states is the main technical advantage of a VSR over a fixed shunt reactor.

A more detailed study of the same offshore system demonstrates how VSR operation can be integrated into a power management scheme rather than relying solely on local voltage measurements [13]. The study includes detection of potentially conflicting control objectives and progressive load shedding when current limits cannot be restored by reactor control alone [13]. The controller and load shedding scheme were validated through hardware in the loop testing. These features are important for offshore constant load applications because they show that VSR performance depends not only on the reactor rating but also on coordinated control of voltage, current, tap sequencing, and equipment limits.

The principal limitation of VSR compensation is that the adjustment mechanism is mechanical and discrete. Tap movement requires sequential switching, so the response is typically seconds rather than the much faster time scale available from power electronic compensators [10]. Song and Kim also demonstrate that VSR-only reactive power control may exhibit a residual steady-state error because the required reactive power cannot always be matched by the discrete available tap positions. Their simulations also show that a VSR may require frequent tap movements when the reactive power reference changes repeatedly and such operation is undesirable because it increases maintenance and lower lifetime of the tap changer [10]. Control response comparison shows that VSR required several seconds to approach a new reactive power reference, while coordinated inverter-based control reduced the fast correction time to the millisecond range and limited unnecessary VSR tap movements [10]. Although that study concerns a wind power plant rather than a constant PQ offshore load but the results remain relevant that a VSR is best suited to large steady state or slowly varying compensation duties.

VSR application also introduces switching and transient constraints that must be evaluated separately from steady state load flow. A 420 kV system study demonstrates that energization behavior depends strongly on the operating tap position, and the investigated reactor produced different inrush and zero sequence current magnitudes at 80 and 150 Mvar, and controlled switching reduced these transient components. De energization of the reactors introduced additional concerns associated with current chopping, transient recovery voltage, overvoltage, and circuit breaker failure [14].

2.3.2 STATCOM Applications

A static synchronous compensator (STATCOM) shown in figure 2, is a shunt-connected power electronic device that uses a voltage-source converter, a DC-link capacitor, and an interfacing transformer to regulate reactive current at the connected AC bus [15]. By controlling the converter voltage and current relative to the network voltage, the STATCOM can continuously absorb or inject reactive power and thereby regulate the bus voltage [15]. This operating principle differs fundamentally from the discrete tap-based response of a VSR because the reactive-current command is not generated through mechanical changes in reactor inductance like in VSR. The STATCOM control system compares the measured bus voltage with its reference value and generates a reactive current command through its control regulators, enabling continuous operation across both the inductive and capacitive regions [15]. This capability is particularly relevant when the required reactive-power correction changes rapidly or when accurate voltage tracking is required.

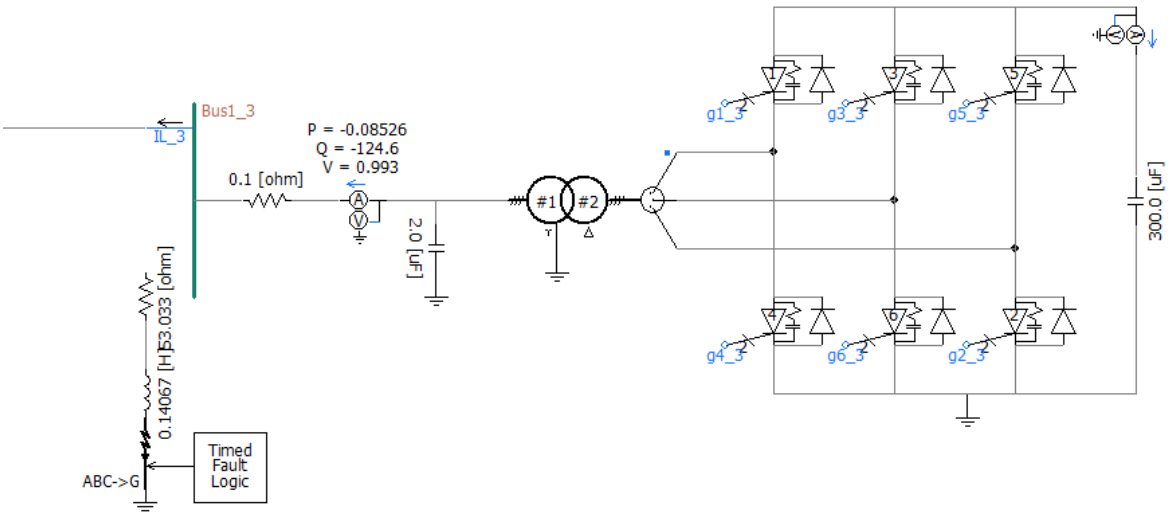


Figure 2: STATCOM schematic from the PSCAD model

For long HVAC submarine links, the primary advantage of a STATCOM is its ability to respond continuously to changes in the cable reactive power balance and terminal voltage, rather than

operating at a fixed compensation level or relying on sequential tap changes. A simulation study examined an offshore wind park connected through a 220 kV HVAC submarine cable and compared compensated and uncompensated operation [15]. With a 70 km cable, the uncompensated case produced excessive reactive power and unacceptable voltage conditions at the 220 kV bus, whereas installation of a STATCOM at the offshore high-voltage bus restored the simulated voltage close to 1.0 p.u. and reduced reactive-power transfer toward the onshore system to approximately zero [15]. The results provide direct evidence that converter-based shunt compensation can regulate both voltage and reactive-power exchange in a long submarine-cable system. However, these findings should be interpreted with caution because the study is based on simulations of variable offshore wind generation rather than the constant-PQ load considered in this thesis. Nevertheless, the underlying capability for continuous reactive-power control remains relevant where cable operating conditions or offshore demand change more rapidly than a mechanically controlled VSR can follow.

The stronger justification for STATCOM installation arises when the compensation requirement extends beyond steady-state absorption of cable charging Mvar to include dynamic voltage support, weak-grid operation, resonance damping, or stability improvement [16]. A study considered a 432 MW offshore wind plant connected through a 220 kV HVAC network comprising two 60 km submarine-cables and a 40 km underground-cable section [16]. The system combined distributed shunt reactors with a 112 MVA STATCOM connected at the onshore terminal, illustrating that the converter was used as a dynamic complement to bulk reactor compensation rather than as the sole absorber of cable-generated reactive power. Small-signal analysis showed that grid-forming control of the STATCOM improved the assessed stability margin relative to grid-following operation in the studied system [16]. This result demonstrates the wider dynamic potential of converter-based compensation in long HVAC networks, where cable capacitance, grid weakness, and converter interactions can create stability challenges.

These dynamic advantages are accompanied by important technical and economic penalties. A STATCOM requires a high-power converter, semiconductor switching devices, a DC-link system, coupling equipment, protection, and coordinated control, making its implementation more

complex than reactor-based compensation. Long HVAC cable systems also exhibit resonance and harmonic-interaction risks, so the control of converter-based devices must be coordinated with cable parameters, shunt reactors, and network strength rather than assessed only through fundamental-frequency load flow. CIGRE Technical Brochure 680 notes that FACTS devices are relatively expensive and are generally justified only when system requirements extend beyond reactive power compensation alone. The brochure also states that a STATCOM is more expensive than an equivalent VSR, despite offering faster response, lower harmonic distortion, and a smaller footprint [3]. For offshore applications, the converter architecture further increases the importance of equipment integration, auxiliary systems, reliability, and maintenance planning. Consequently, the technical superiority of fast continuous control does not automatically make STATCOM the preferred solution for every long submarine cable. For a system supplying a stable constant-PQ load, the key question is whether the improved dynamic performance of a STATCOM justifies its additional cost and complexity compared with a VSR.

Table 2: Comparative characteristics of VSR and STATCOM compensation for long HVAC submarine cables [3], [8] [4] [12]

Criterion	**VSR**	**STATCOM**
Operating principle	Variable inductive reactor	VSC-based shunt compensator
Reactive-power control	Discrete tap-based absorption of VAR	Continuous absorption and injection of VAR
Response speed	Seconds-scale, mechanically limited	Fast electronic response
Bulk cable-charging compensation	Well suited	Technically capable
Dynamic voltage support	Limited	Strong
Control resolution	Discrete	Continuous
Steady-state losses	Generally low	higher
Mechanical components	OLTC and reactor mechanism	No mechanical VAR control
Power-electronic complexity	Low	High
Switching/transient concerns	Tap position, energization, inrush, zero-missing	Converter interactions, harmonics, control stability
Cooling and auxiliaries	Relatively limited	Significant converter auxiliaries and cooling

Maintenance focus	OLTC wear and reactor equipment	Semiconductors, cooling, controls, auxiliaries
CAPEX	Generally lower	Generally higher
Best technical role	Persistent and slowly varying compensation	Fast and continuous voltage support

Table 2 indicates that VSR and STATCOM technologies address several aspects of the compensation problem. VSRs are naturally suited to persistent and slowly varying capacitive reactive-power requirements because they provide adjustable bulk inductive absorption with relatively simple power-system integration. Their main limitations arise from discrete tap resolution, mechanical operating speed, and switching constraints. STATCOMs provide continuous bidirectional reactive-power control and substantially faster dynamic support, making them more suitable where rapid voltage correction, weak-grid operation, or stability support is required. These benefits, however, are accompanied by greater converter complexity, higher capital cost, and additional losses and auxiliary requirements. For long HVAC submarine links supplying offshore constant-PQ loads, the preferred technology therefore depends on whether the dominant requirement is economical steady-state compensation or fast dynamic voltage support. This distinction forms the basis for the research gap developed in the following section.

2.4 Identified Research Gap

The reviewed literature provides substantial evidence on the individual capabilities of VSR and STATCOM technologies, but direct comparison between them under equivalent offshore HVAC operating conditions remains limited. VSR studies primarily examine adjustable bulk compensation, OLTC coordination, voltage regulation, cable-current management, and switching behavior while STATCOM studies more commonly emphasize continuous reactive-power control, dynamic voltage support, fault response, and stability under weak-grid conditions. Therefore, literature review studies assess the two technologies using different systems, objectives, disturbance scenarios, and performance criteria which make their results difficult to compare directly. Within the literature reviewed in this chapter, a consistent assessment was not

identified in which VSR and STATCOM alternatives are evaluated using the same submarine cable parameters and system.

A second limitation concerns the operating context addressed by many recent offshore compensation literatures. Several studies focus on offshore wind power plants, where variable generation, converter interfaced turbines, grid code compliance, and weak grid stability strongly influence the value of dynamic reactive power support. Long HVAC submarine cables supplying offshore industrial facilities present a different operating environment, as the receiving-end system is typically characterized by relatively stable active and reactive power demands. Existing studies on offshore oil and gas applications highlight the importance of shunt reactor placement, VSR coordination, cable current supervision, load shedding, and switching constraints. However, none provides a direct technical and life cycle cost comparison between VSR and STATCOM compensation under identical offshore load and cable conditions. Consequently, the reviewed literature provides limited evidence on whether the faster response and continuous controllability of a STATCOM offers sufficient additional benefit to justify its greater complexity for offshore constant PQ loads.

These limitations indicate the need for a common technical and economic assessment framework in which VSR and STATCOM options are evaluated under the same assumptions. This gap motivates the present thesis, which compares both technologies for long HVAC submarine cables supplying offshore constant PQ loads using a common technical and life cycle cost assessment framework.

Chapter 3
Methodology and System Modeling

This chapter presents the methodology used to compare VSR and STATCOM compensation for the 230 kV offshore HVAC submarine cable system studied. The analysis is based on an industrial PSCAD model and considers a long double circuit submarine link supplying a constant PQ offshore load under light and full load operating conditions. The chapter first defines the research framework and principal system configuration and then describes the cable, load, VSR, and STATCOM representations used in the simulations. Finally, the common assessment procedure is established for comparing steady state voltage performance, resonance characteristics, transient recovery voltage, and response to sudden changes in load. The resulting technical performance is evaluated in Chapter 4, while the life cycle cost comparison is developed separately in Chapter 5.

3.1 Research Framework and System Description

The objective of this study is to compare the technical performance of variable shunt reactor (VSR) and static synchronous compensator (STATCOM) for a long 230 kV HVAC submarine transmission link supplying a constant PQ offshore industrial load. The comparison is performed using the same underlying industrial power system model, cable configuration, operating conditions, and voltage performance criterion so that differences in system behavior can be associated primarily with the selected compensation technology. The study is implemented in PSCAD Version 4.6 and considers three principal configurations: an uncompensated baseline, the VSR compensated system, and a modified STATCOM compensated system. Technical performance is examined under light and full load conditions through steady state, resonance, switching/transient, and disturbance response assessments.

The investigated network is based on an industrial offshore HVAC system comprising two 230 kV submarine cable circuits operated simultaneously between the onshore and offshore systems. Each circuit contains an approximately 88.3 km principal submarine route formed by two main cable sections with different conductor cross sections. The offshore demand is represented as a

constant PQ load, and two operating conditions are considered: 10% loading and 100% loading. The principal system and operating parameters are summarized in Table 3. Although the complete PSCAD model includes the associated upstream network, transformers, transition sections, and offshore distribution system, the present study focuses on the electrical behavior of the long submarine cable and the connected reactive power compensation devices.

Table 3: Principal parameters of the studied offshore HVAC system

Parameter	**Value**
Nominal transmission voltage	230 kV
System frequency	60 Hz
Number of submarine circuits	2
Circuit operating condition	Both circuits in simultaneous operation
Principal submarine cable length per circuit	88.30 km
1000 mm² cable section length	29.58 km
630 mm² cable section length	58.72 km
Offshore load representation	Constant PQ
Full load active power	261.850 MW
Full load reactive power	49.465 MVAr
10% load active power	26.185 MW
10% load reactive power	4.947 MVAr
Studied load levels	10% and 100%
Simulation software	PSCAD Version 4.6

A simplified representation of the studied system is in Figure 3. To improve clarity, the figure should be presented as two separate subfigures, illustrating the VSR and STATCOM configurations independently. Both subfigures should retain the same double-circuit submarine cable configuration so that the differences between the compensation arrangements are immediately apparent. The VSR configuration shows the two onshore bus connected reactors, two onshore line connected reactors, and two offshore line connected reactors. The STATCOM configuration shows two onshore and two offshore STATCOM units, with no VSR remaining in the system. The offshore constant PQ load also included in both subfigures.

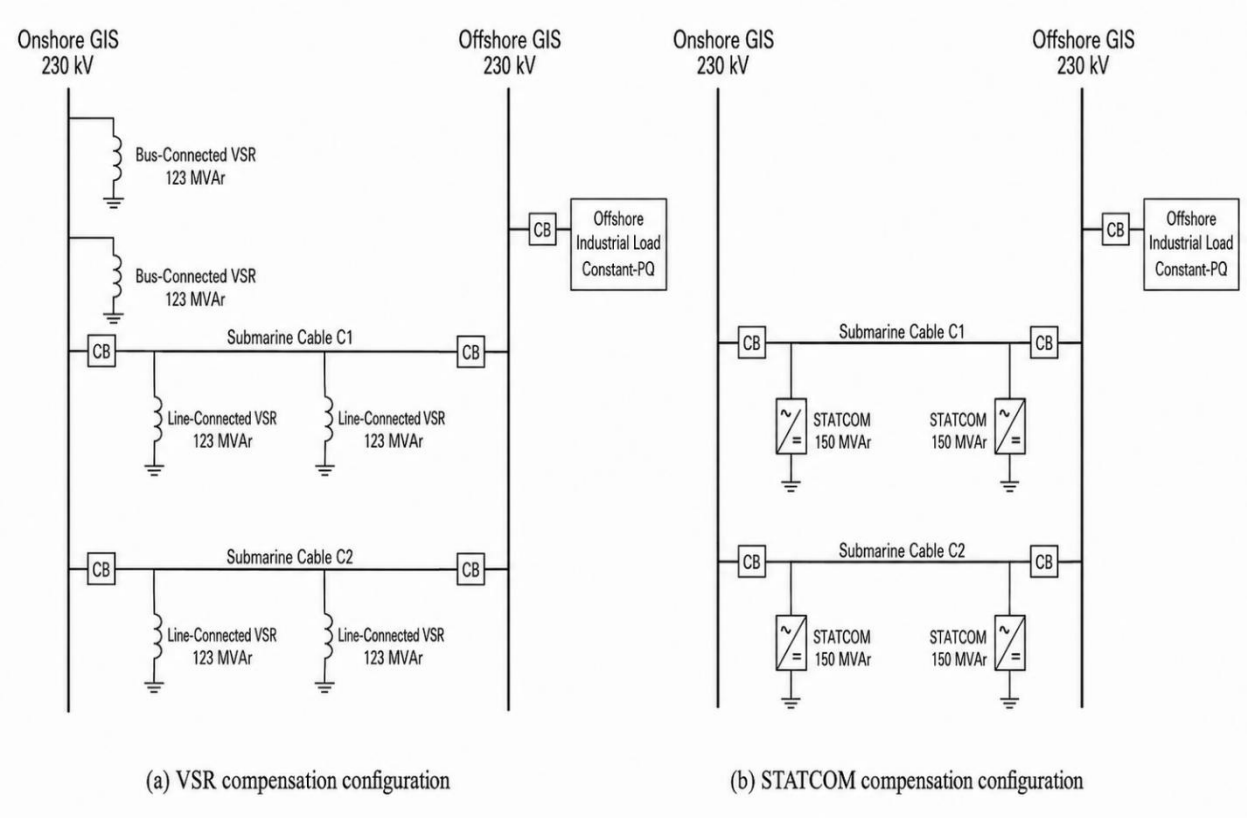


Figure 3: Simplified single line diagrams of the 230 kV offshore HVAC system studied: (a) VSR compensation configuration and (b) STATCOM compensation configuration.

The VSR configuration represents an industrial compensation arrangement and retains the original equipment ratings without re-sizing. The system includes six 123 MVAr VSR units: two bus-connected reactors at the onshore 230 kV bus, two line-connected reactors at the onshore cable terminals, and two line-connected reactors at the offshore cable terminals. In the alternative STATCOM configuration, the two onshore bus connected VSRs are removed and the four remaining lines connected VSR positions are replaced by four STATCOM units. Two STATCOMs are installed onshore and two offshore, with each unit rated at 150 MVAr. No VSR remains in the STATCOM case. The resulting compensation arrangements are summarized in Table 4.

Table 4: Compensation configurations considered in the comparative study

Feature	VSR configuration	STATCOM configuration
Onshore bus connected devices	2 × 123 MVAr VSR	None
Onshore terminal devices	2 × 123 MVAr VSR	2 × 150 MVAr STATCOM
Offshore terminal devices	2 × 123 MVAr VSR	2 × 150 MVAr STATCOM
Total number of compensation devices	6	4
Unit rating	123 MVAr Y connected	150 MVAr
Rating basis	industrial design	Iterative simulation sizing
Reactive power control characteristic	Adjustable tap based inductive compensation	Controllable shunt reactive power support
VSR retained in configuration	Yes	No

The VSR case therefore has an industrial design and its installed compensation capacity, whereas the STATCOM case represents a complete replacement of the controllable reactor arrangement at the four line terminal locations. The STATCOM rating was determined iteratively by increasing the available reactive power capacity until the studied system satisfied the adopted steady state voltage criterion of 0.95–1.05 p.u. The STATCOM model is conservatively described as providing controllable shunt reactive power support, as a detailed investigation of its internal control strategy is beyond the scope of the present study.

To maintain a consistent comparative basis, the uncompensated, VSR, and STATCOM configurations are evaluated using the same two submarine circuits, offshore constant PQ load definition, 10% and 100% operating points, and underlying PSCAD network model. The uncompensated case is used as the baseline for identifying the inherent electrical behavior of the long HVAC cable system. The VSR and STATCOM alternatives are then assessed under equivalent system conditions. The broader technical framework considers steady state behavior, resonance characteristics, switching and transient performance, and disturbance response, while the detailed component models and PSCAD implementation are presented in Section 3.2. The

specific assessment procedures and performance criteria used for the comparison are defined in Section 3.3.

3.2 Component and Simulation Modeling

The submarine cable sections were represented in PSCAD using the frequency dependent phase model to capture the distributed and frequency dependent behavior of the long HVAC link. This modeling approach is suitable for electromagnetic transient studies because cable resistance, inductance, and capacitance are represented as distributed quantities whose effective behavior varies with frequency, rather than as a single lumped network at the fundamental frequency [17]. The investigated route contains two principal cable sections per circuit: a 58.72 km section with a 630 mm² conductor and a 29.58 km section with a 1000 mm² conductor. Their per kilometer electrical parameters are summarized in Table 5. The offshore industrial demand was represented as a constant PQ load using the two operating points defined in Section 3.1: 261.850 MW and 49.465 MVAr at 100% loading, and 26.185 MW and 4.947 MVAr at 10% loading. This representation maintains fixed active and reactive power at each selected operating point and allows the effect of cable charging behavior and compensation technology to be compared under common load conditions.

Table 5: Electrical parameters of the principal submarine cable sections

Parameter	**630 mm² section**	**1000 mm² section**
Section length	58.72 km	29.58 km
Resistance, R	0.0402 Ω/km	0.0284 Ω/km
Inductance, L	0.416 mH/km	0.388 mH/km
Capacitance, C	0.166 µF/km	0.197 µF/km
Nominal voltage	230 kV	230 kV

The VSR reactors were represented as manual adjustable inductive compensation devices whose reactive power absorption changes discretely through tap operation. This is consistent with practical VSR operation, in which a tap changer modifies the reactor rating in steps rather than providing continuously variable output [18]. In the implemented model, the onshore units use

33 tap positions, and the offshore units use 25 tap positions, with a nominal step size of 2.5%. The distinction between bus connected and line connected units was also preserved because reactor connection location influences the way reactive power and voltage are controlled across the transmission system [18].

For the alternative compensation case, the VSR arrangement was replaced by four STATCOM units, with two connected onshore and two offshore through coupling transformers. Each STATCOM was assigned to a reactive power operating range of −150 to +150 MVAr and was configured to provide controllable shunt reactive power support. This representation is consistent with the transmission STATCOM concept defined in IEEE Std 1052 2018, in which a shunt connected voltage source converter system provides controllable inductive or capacitive current and may be interfaced with the AC network through a dedicated coupling transformer [12]. The detailed internal control mode is not reproduced here because the present study focuses on the system level effect of the compensation device rather than converter controller design. The 150 MVAr unit rating was determined iteratively by increasing the available reactive power capacity until the studied operating cases satisfied the adopted steady state voltage criterion of 0.95–1.05 p.u. This procedure provides a practical basis for comparing the VSR configuration with a STATCOM alternative capable of meeting the same overall voltage performance requirement.

3.3 Comparative Assessment Method

The VSR and STATCOM configurations were evaluated using the same underlying PSCAD network model and the same 10% and 100% load. An uncompensated case was first established as a common baseline to evaluate the fundamental behavior of the long HVAC submarine cable system. The compensated configurations were then assessed under equivalent conditions, with particular attention to the steady state voltage profile along the cable. A normal operating range of 0.95–1.05 p.u. was adopted as the principal steady state voltage criterion, allowing the ability of each compensation technology to control cable related voltage rise and maintain acceptable terminal and internal voltages to be compared directly.

The assessment also included zero sequence frequency scans and transient recovery voltage (TRV) studies. The frequency scans were used to identify the dominant resonance frequencies and associated impedance peaks at the onshore and offshore buses under both load conditions. For the TRV assessment, four offshore fault types were considered: three phase, single line to ground, line to line to ground, and line to line faults. The simulated transient recovery voltage (TRV) peaks were assessed against the breaker capability limits of 562 kV for the onshore breaker and 472 kV for the offshore breaker, as specified in the project design specifications. Applying the same fault types and loading conditions to both compensation configurations provided a consistent basis for comparing their influence on switching and transient stresses.

Dynamic operating response was further examined through a sudden load loss case in which approximately 20 MVA of load was disconnected at the 100% loading condition for both the VSR and STATCOM configurations. The resulting voltage response was used to compare the ability of the two compensation technologies to maintain acceptable system behavior following a rapid change in demand. In addition, VSR specific tap change operation was simulated separately to assess the effect of discrete compensation adjustment on the system voltage.

Chapter 4
Technical Results and Discussion

This chapter presents the technical results obtained from the PSCAD simulations of the uncompensated, VSR compensated, and STATCOM compensated configurations. The comparison focuses on steady state voltage performance, zero sequence frequency scan behavior, transient recovery voltage, and response to sudden load changes. The same cable system, load conditions, and assessment criteria were used for the VSR and STATCOM cases to allow a consistent comparison between the two compensation technologies.

4.1 Steady State Voltage Performance

The uncompensated baseline case was first simulated to identify the natural behavior of the long HVAC submarine cable without reactive power compensation. The results in figures 4, 5 and 6 show a clear voltage rise along the cable. The sending end voltage reaches approximately 255 kV, equivalent to 1.11 p.u., while the receiving end voltage reaches approximately 264 kV, equivalent

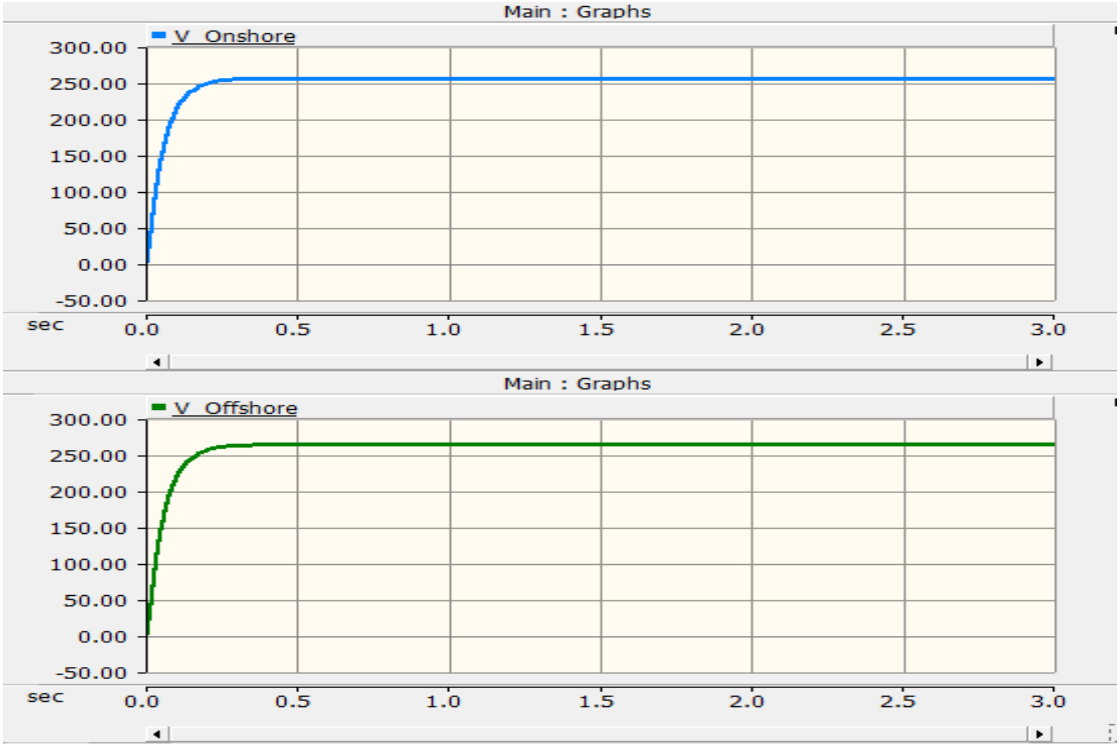


Figure 4: Uncompensated voltage response at the onshore and offshore terminals.

to 1.15 p.u. This exceeds the adopted upper voltage limit of 1.05 p.u., confirming that compensation is required for this system.

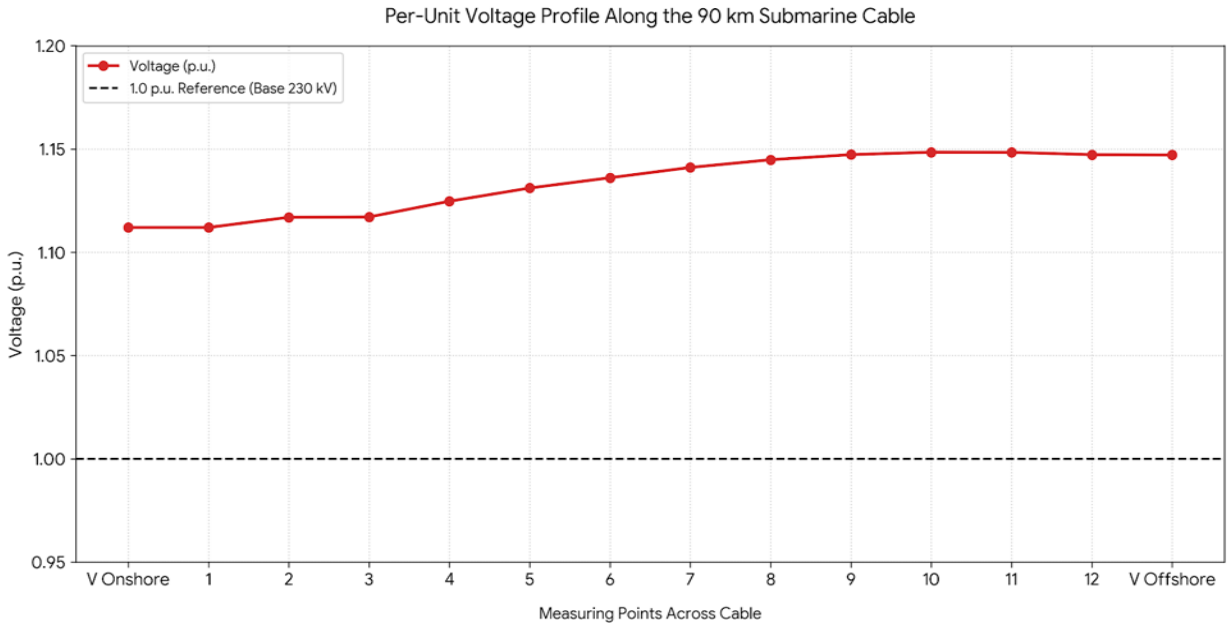


Figure 5: Uncompensated voltage profile along the submarine cable.

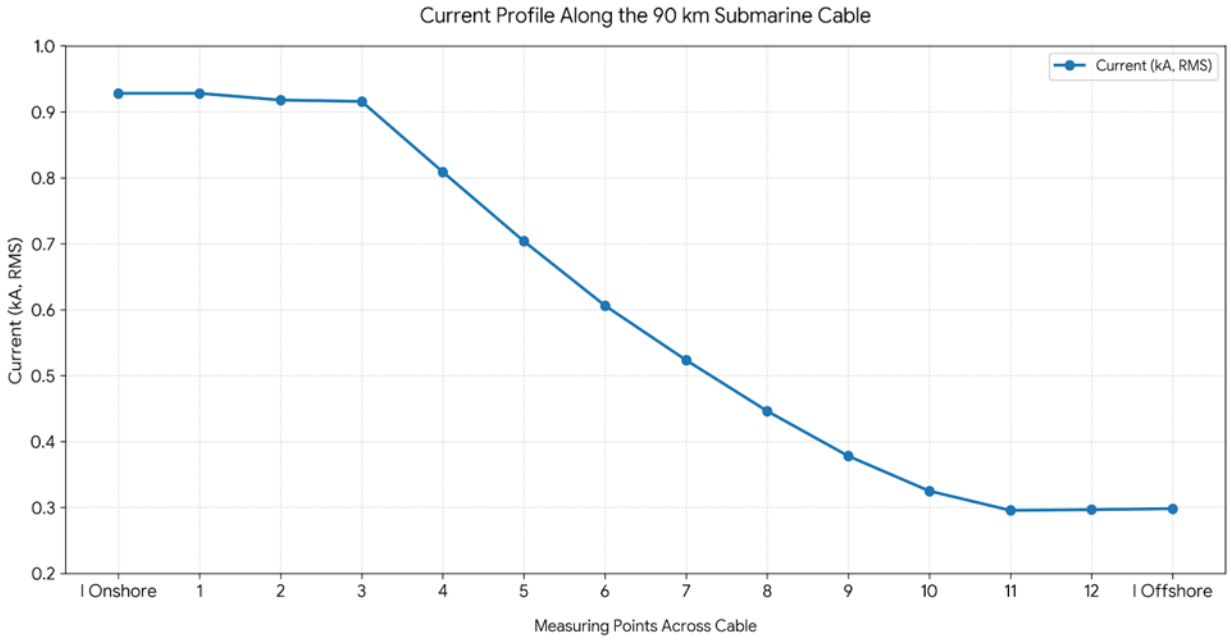


Figure 6: Uncompensated current profile along the submarine cable.

After installing VSR compensation, the voltage profile was reduced to within the acceptable operating range. At 10% loading, the sending end voltage is approximately 229 kV, or 0.996 p.u., while the receiving end voltage is approximately 232 kV, or 1.01 p.u as shown in figures 7 and 8. At 100% loading, figures 9 and 10 clearly shows the sending end voltage is approximately 230 kV, or 1.0 p.u., while the receiving end voltage is approximately 233 kV, or 1.01 p.u. Therefore, the VSR configuration successfully controls the cable voltage rise at both light load and full load operation.

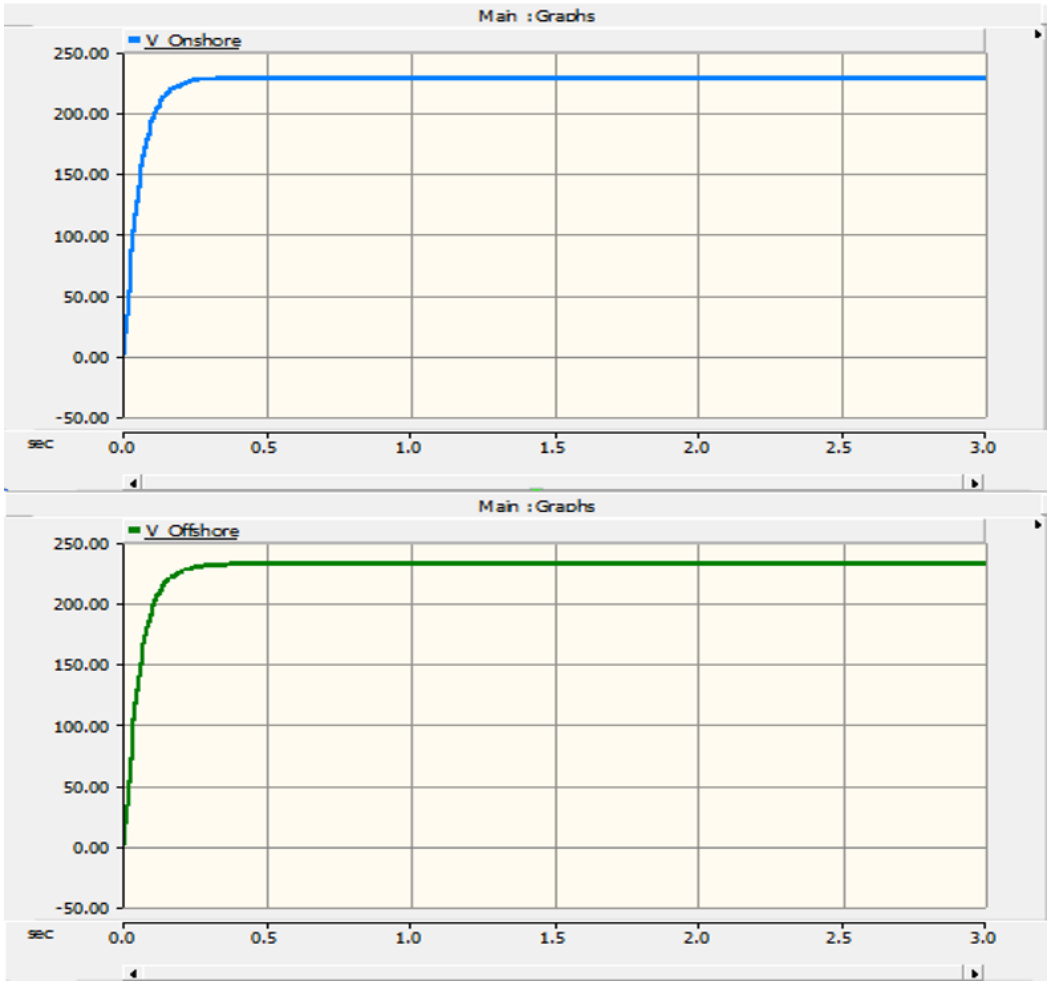


Figure 7: Steady state voltage response with VSR compensation at 10% loading.

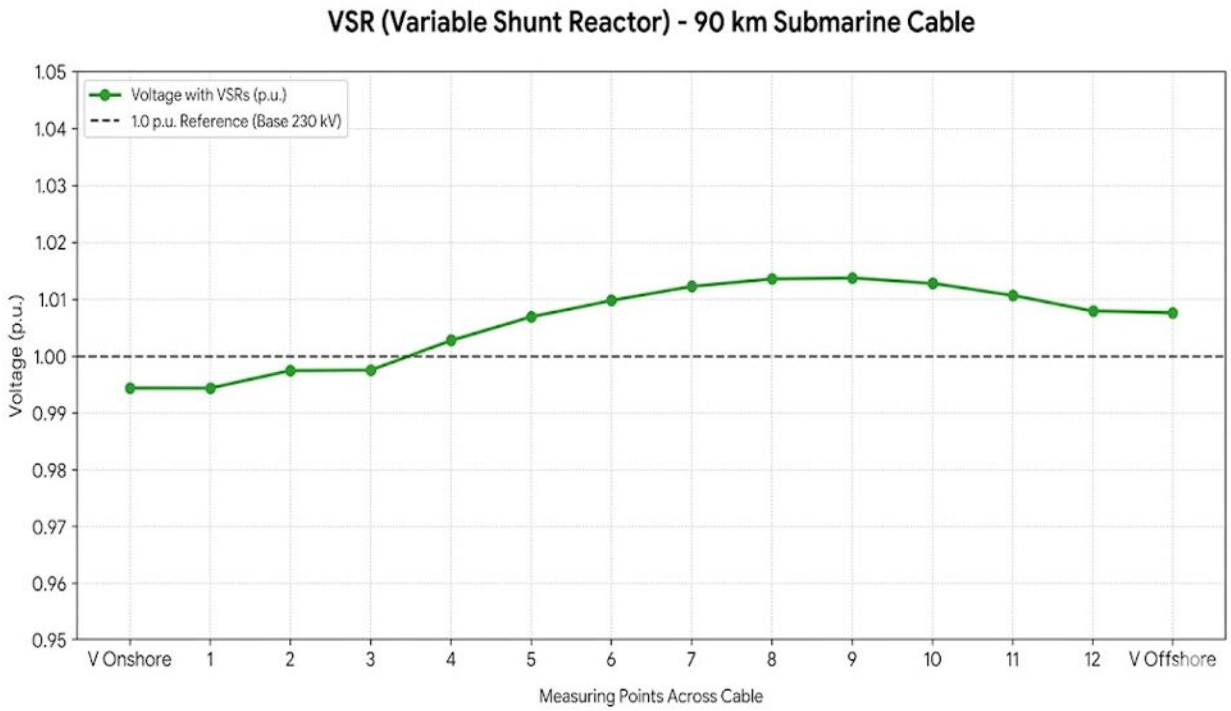


Figure 8: Voltage profile along the submarine cable with VSR compensation at 10% loading.

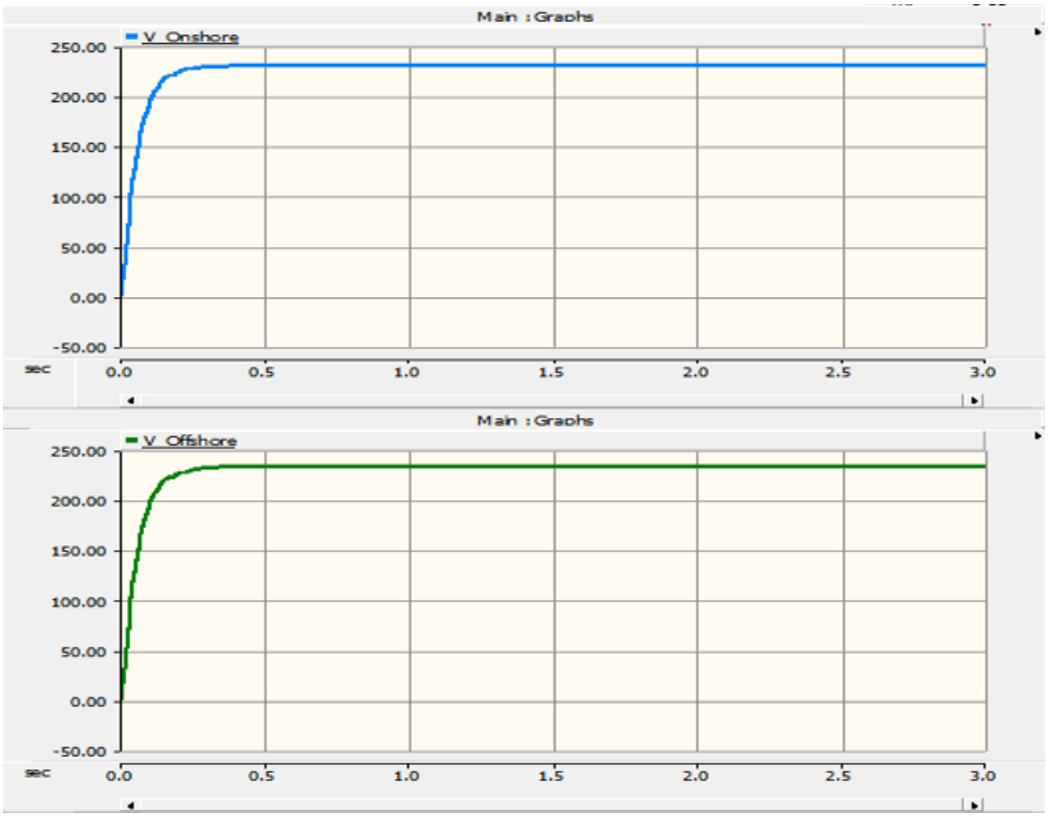


Figure 9: Steady state voltage response with VSR compensation at 100% loading.

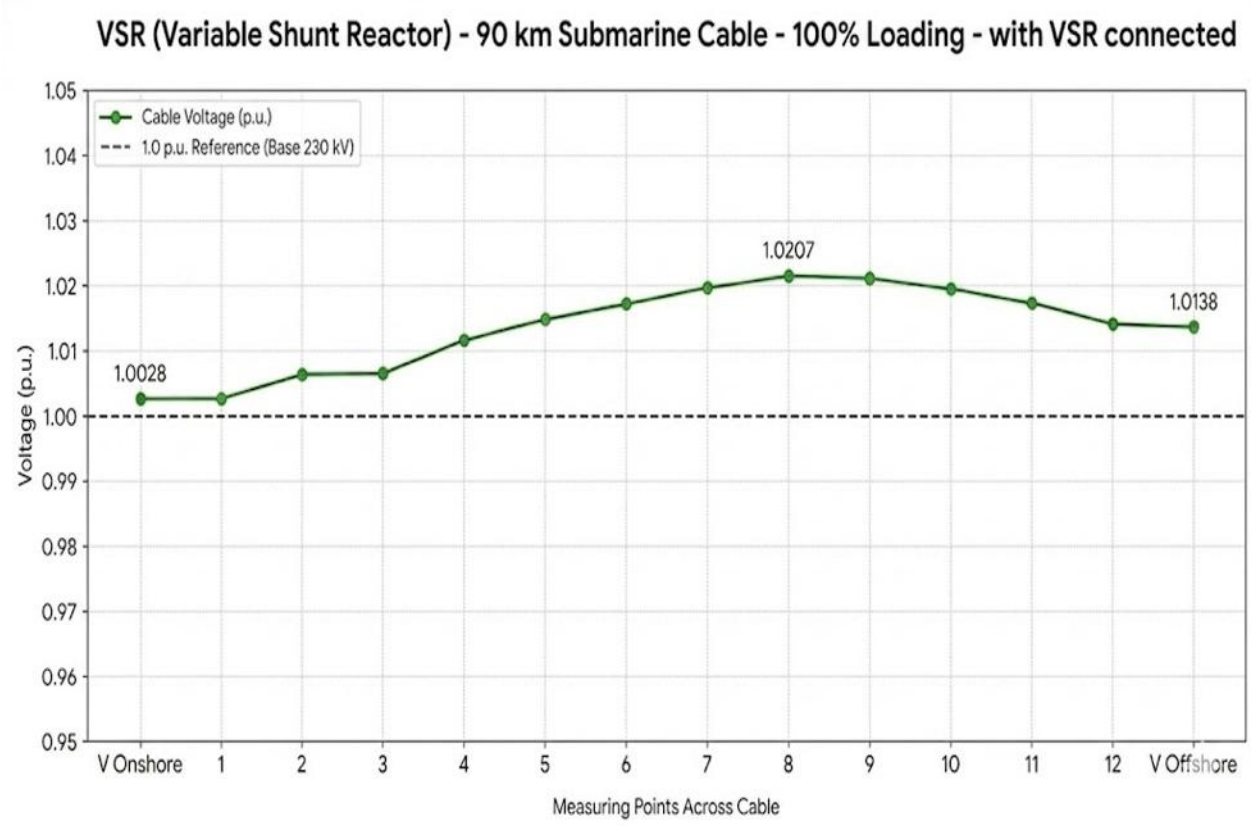


Figure 10: Voltage profile along the submarine cable with VSR compensation at 100% loading.

The STATCOM configuration also maintains the system voltage within the required range. At 10% loading shown in figures 11 and 12, the sending end and receiving end voltages are both close to 1.01 p.u. At 100% loading, figures 13 and 14 show the sending end voltage is approximately 231 kV, while the receiving end voltage is approximately 229 kV. The maximum cable voltage remains below the 1.05 p.u. limit in both STATCOM cases.

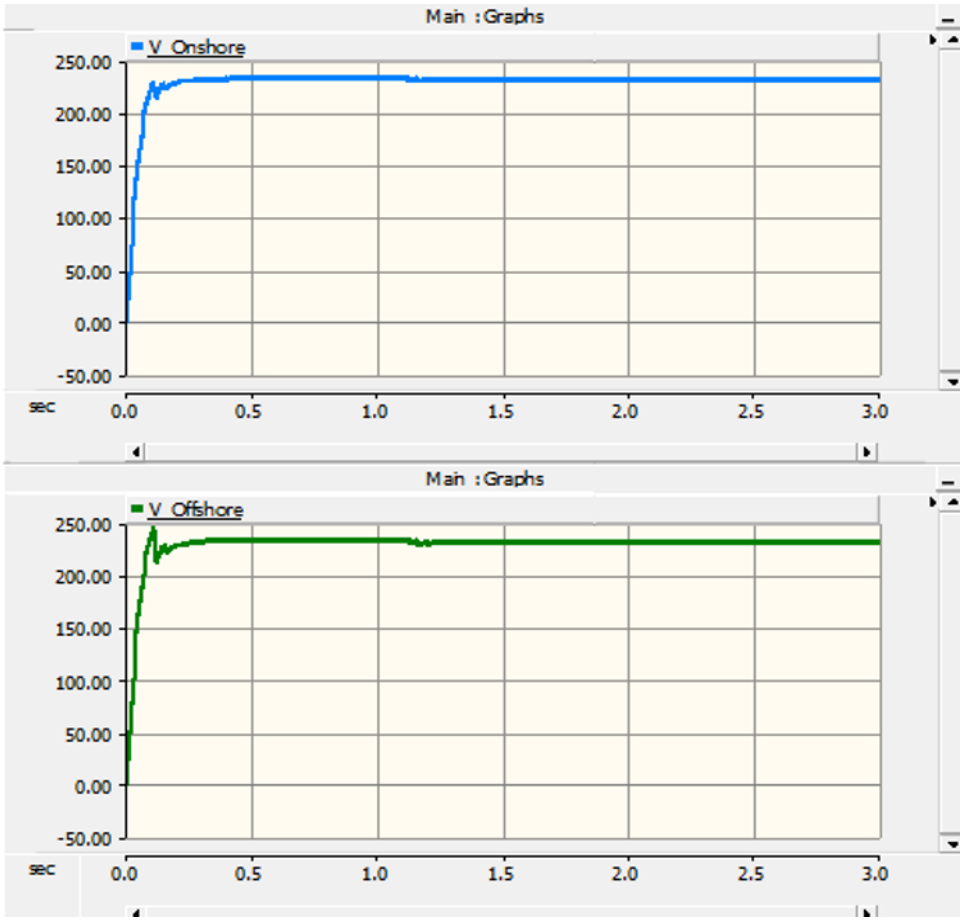


Figure 11: Steady state voltage response with STATCOM compensation at 10% loading.

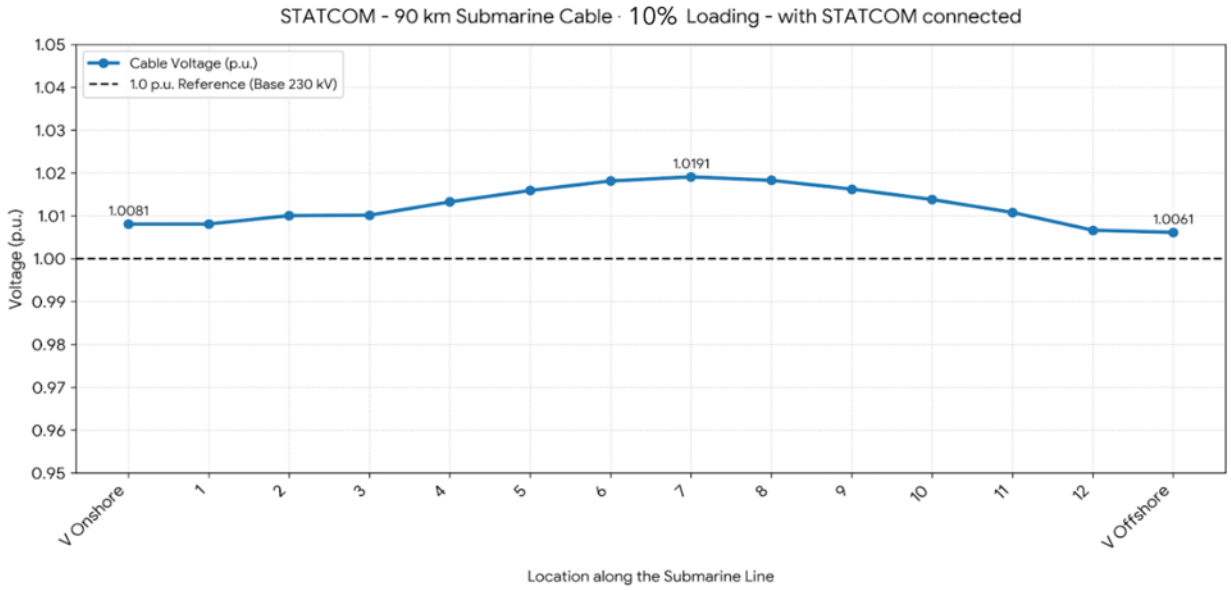


Figure 12: Voltage profile along the submarine cable with STATCOM compensation at 10% loading.

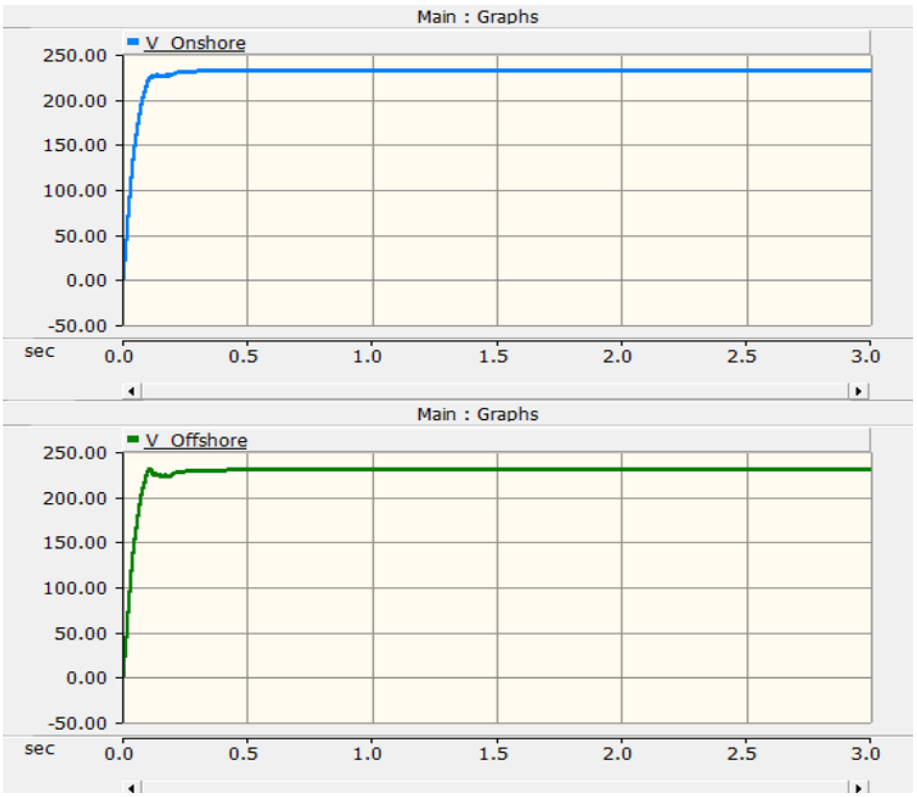


Figure 13: Steady state voltage response with STATCOM compensation at 100% loading.

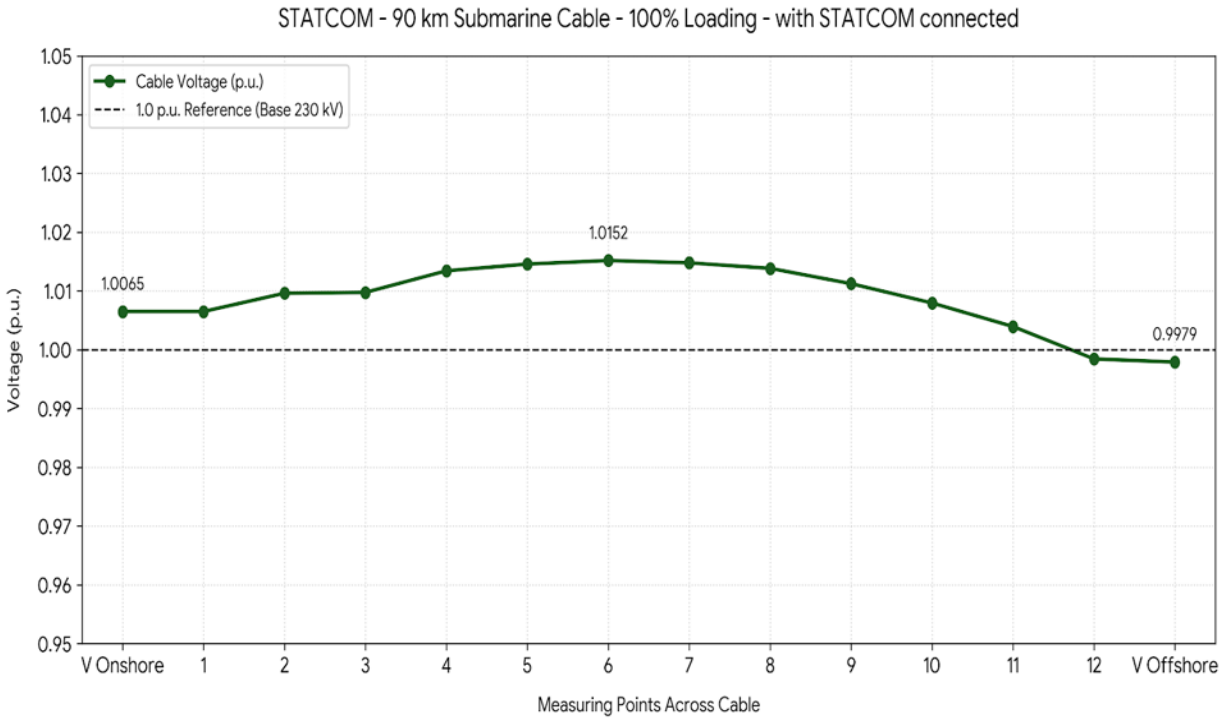


Figure 14: Voltage profile along the submarine cable with STATCOM compensation at 100% loading.

The steady state voltage results are summarized in Table 6. Both VSR and STATCOM compensation eliminate the excessive voltage rise observed in the uncompensated case. The STATCOM case gives a slightly flatter voltage profile at full load, while the VSR case also remains comfortably within the required voltage range.

Table 6: Steady state voltage comparison

Case	**Onshore voltage**	**Offshore voltage**	**Maximum cable voltage**	**Assessment**
Uncompensated	1.11 p.u.	1.15 p.u.	1.15 p.u.	Exceeds limit
VSR, 10% loading	0.996 p.u.	1.01 p.u.	1.01 p.u.	Acceptable
VSR, 100% loading	1.00 p.u.	1.01 p.u.	1.02 p.u.	Acceptable
STATCOM, 10% loading	1.01 p.u.	1.01 p.u.	1.019 p.u.	Acceptable
STATCOM, 100% loading	1.006 p.u.	0.998 p.u.	1.015 p.u.	Acceptable

4.2 Zero Sequence Frequency Scan Results

Zero sequence frequency scans were performed on the onshore and offshore buses to identify the dominant driving point impedance peaks and compare the resonance characteristics of the VSR and STATCOM configurations. Frequency scan analysis is commonly used to identify bus driving point impedance magnitude and resonance frequencies in power system harmonic studies [19]. The purpose of this assessment was to identify the dominant impedance peaks and evaluate how the VSR and STATCOM configurations influence the system's resonance characteristics.

At 10% loading, the VSR configuration shown in figures 15 and 16 shows a dominant zero sequence impedance peak at approximately 104 Hz onshore and 114 Hz offshore. The corresponding impedance peaks are approximately 220 Ω and 251 Ω, respectively. In comparison, the STATCOM configuration shifts the dominant peak to a higher frequency, approximately 157 Hz onshore and 156 Hz offshore. The impedance peaks are approximately 214 Ω onshore and 309 Ω offshore.

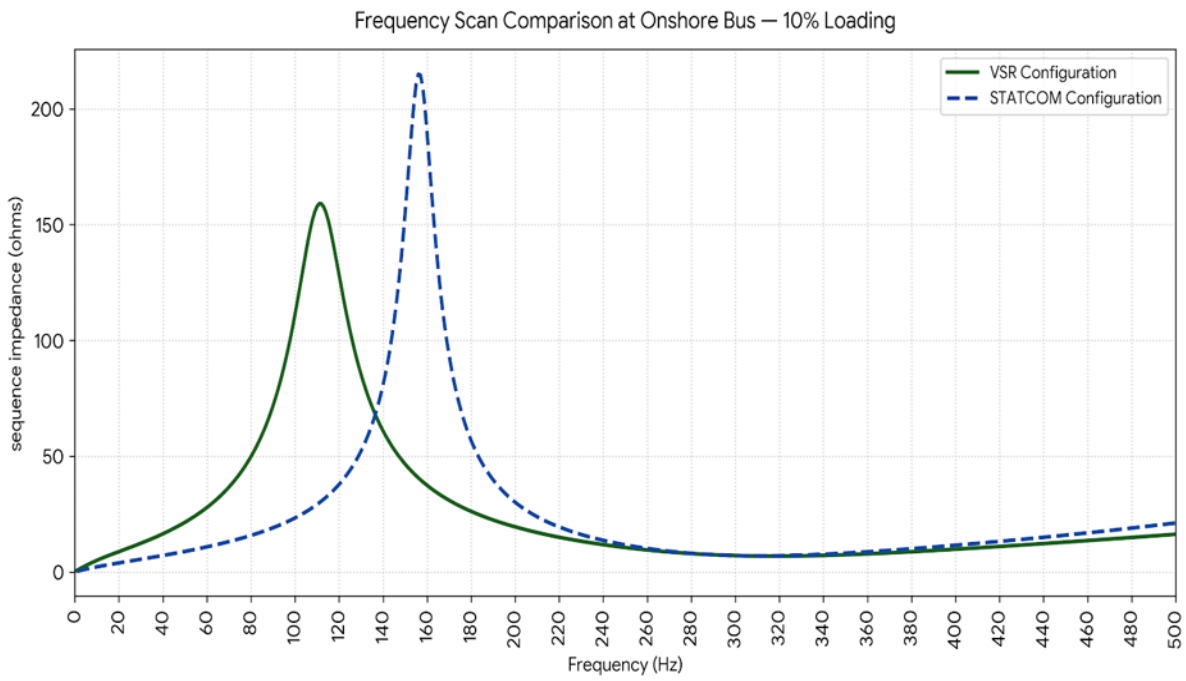


Figure 15: Zero sequence frequency scan comparison at 10% loading at onshore bus.

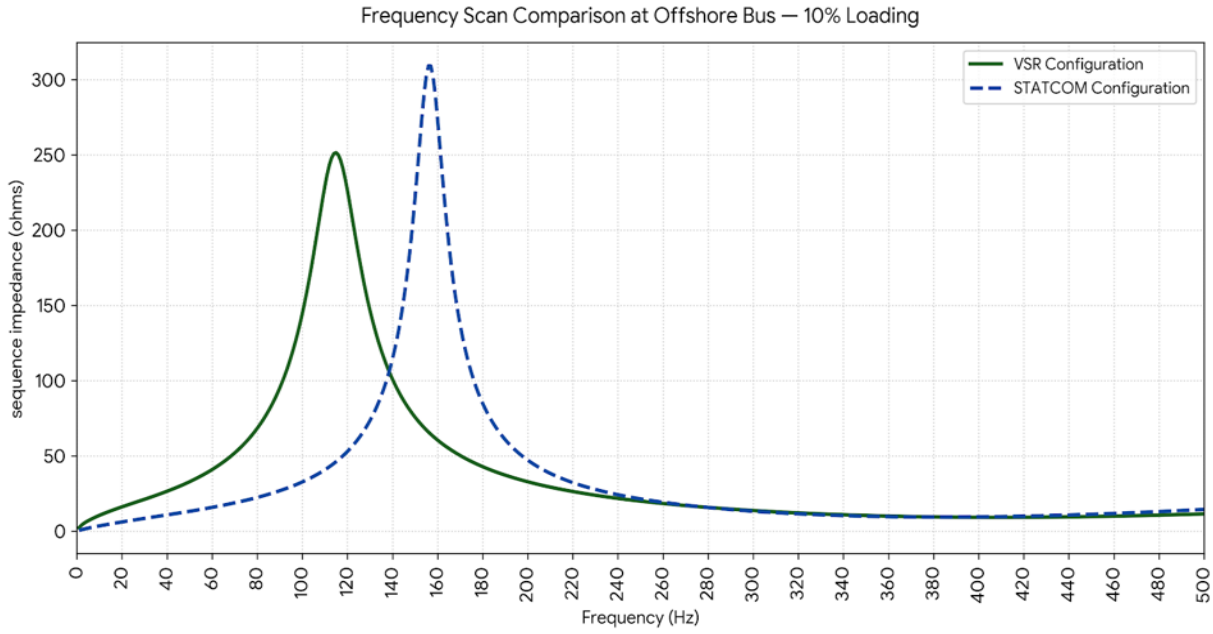


Figure 16: Zero sequence frequency scan comparison at 10% loading at offshore bus.

At 100% loading shown in figures 17 and 18, the VSR configuration has a dominant peak at approximately 111 Hz at both the onshore and offshore buses. The impedance peak is

approximately 159 Ω onshore and 237 Ω offshore. For the STATCOM configuration, the dominant peak remains close to 156 Hz, with impedance peaks of approximately 215 Ω onshore and 309 Ω offshore.

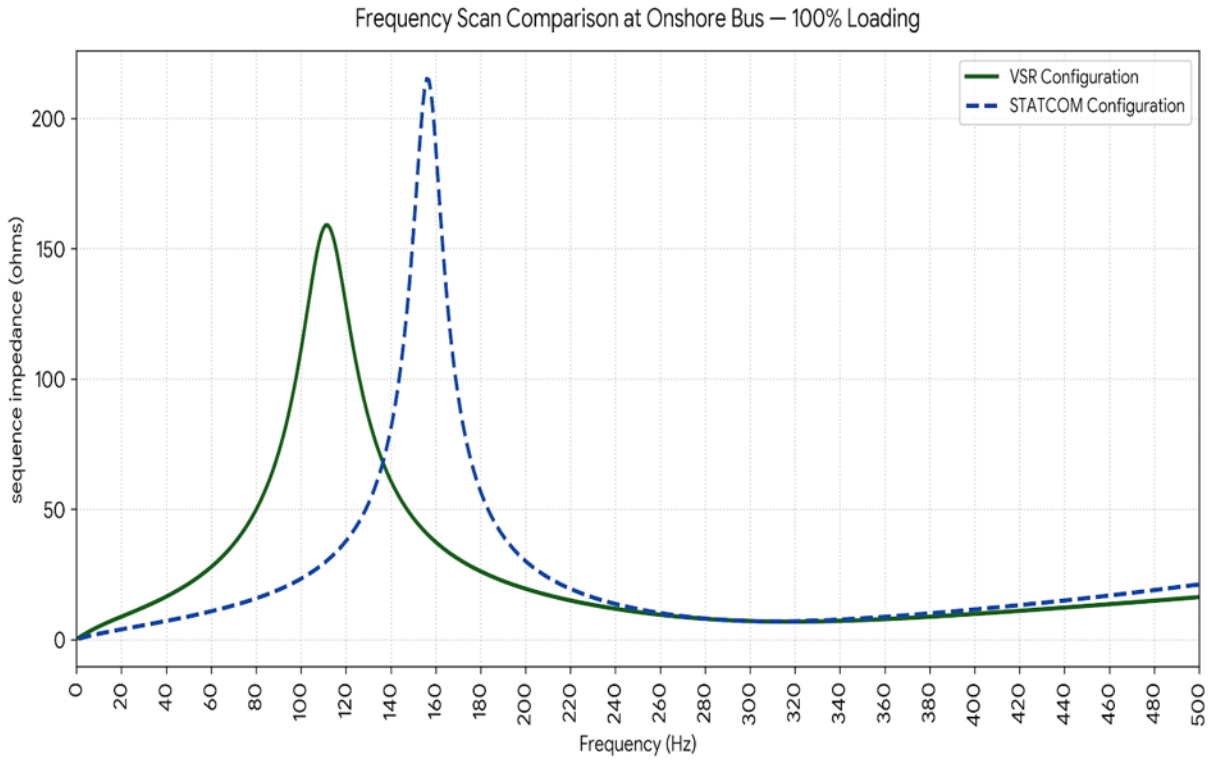


Figure 17: Zero sequence frequency scan comparison at 100% loading at onshore bus.

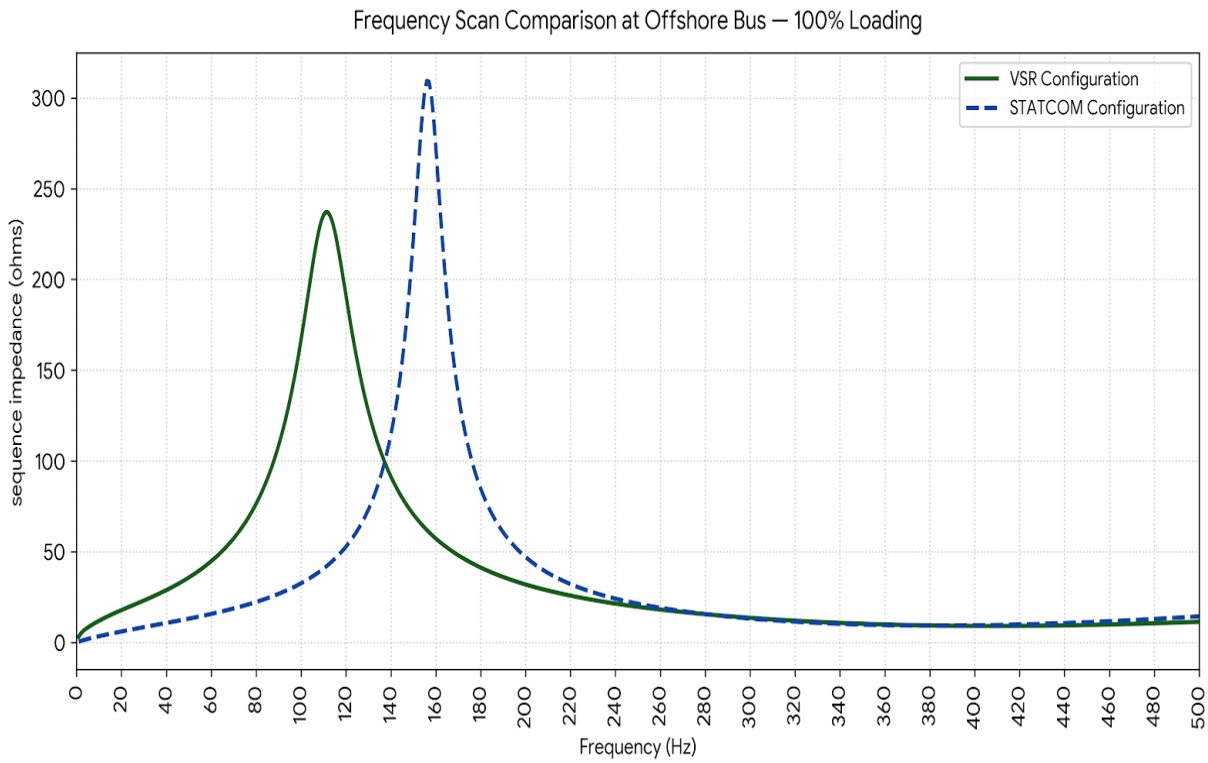


Figure 18: Zero sequence frequency scan comparison at 100% loading at offshore bus.

Table 7: Zero sequence frequency scan comparison

Loading	Configuration	Onshore peak	Offshore peak
10%	VSR	104 Hz, 220 Ω	114 Hz, 251 Ω
10%	STATCOM	157 Hz, 214 Ω	156 Hz, 309 Ω
100%	VSR	111 Hz, 159 Ω	111 Hz, 237 Ω
100%	STATCOM	156 Hz, 215 Ω	156 Hz, 309 Ω

The results show that the compensation technology changes the zero sequence resonance characteristic of the system. The VSR configuration produces the dominant impedance peak at a lower frequency, while the STATCOM configuration shifts the dominant peak to a higher frequency. The offshore bus generally exhibits a higher impedance peak than the onshore bus. To evaluate the importance of the identified STATCOM resonance peaks at a relevant zero-sequence harmonic, a screening level equal to 0.707 of each dominant impedance peak was adopted similar as band pass filters. Since zero-sequence harmonic currents are associated with triplen harmonics, the third harmonic at 180 Hz was selected as the principal assessment

frequency within the scanned range. At 10% loading, the onshore impedance at the third harmonic is approximately 51 Ω compared with a peak of 214 Ω, while the offshore impedance is 73 Ω compared with a peak of 309 Ω. At 100% loading, the corresponding values are 54 Ω versus 215 Ω onshore and 78 Ω versus 309 Ω offshore. In all cases, the third-harmonic impedance remains well below the respective 0.707 threshold of approximately 151–152 Ω onshore and 219 Ω offshore. Therefore, the third harmonic is outside the dominant high-impedance resonance region for the studied STATCOM cases.

Therefore, the frequency-scan results are considered very low risk on the system for the studied cases. However, the peaks still identify frequency ranges that should be noted, particularly if future system changes introduce harmonic or transient excitation near these frequencies.

4.3 Transient Recovery Voltage Performance

Transient recovery voltage (TRV) was assessed because recovery voltage is a key circuit breaker stress during fault interruption and is used in making and breaking test assessment for high voltage circuit breakers [20]. Transient recovery voltage was assessed for offshore faults under both 10% and 100% loading. Four fault types were considered: three phase, single line to ground, line to line to ground, and line to line faults. The simulated TRV peaks were compared with the breaker capability limits of 472 kV for the offshore breaker and 562 kV for the onshore breaker.

For the VSR configuration at 10% loading, all TRV values remain below the breaker capability limits as shown in figures 19, 20, 21 and 22. The highest offshore TRV is 282 kV for the three-phase fault, while the highest onshore TRV is 414 kV, also for the three-phase fault. Both values are below their corresponding limits.

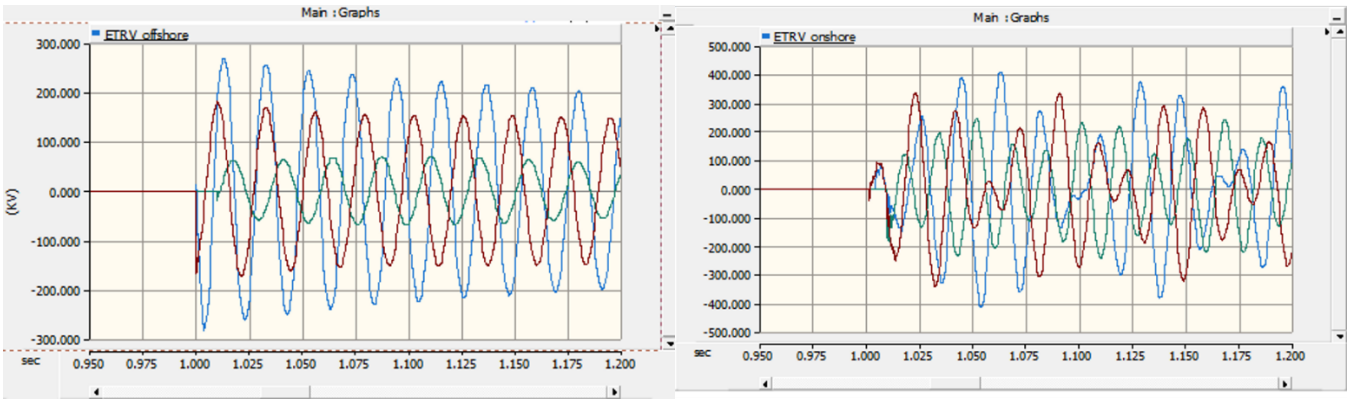


Figure 19: VSR TRV response for offshore 3ph fault at 10% loading.

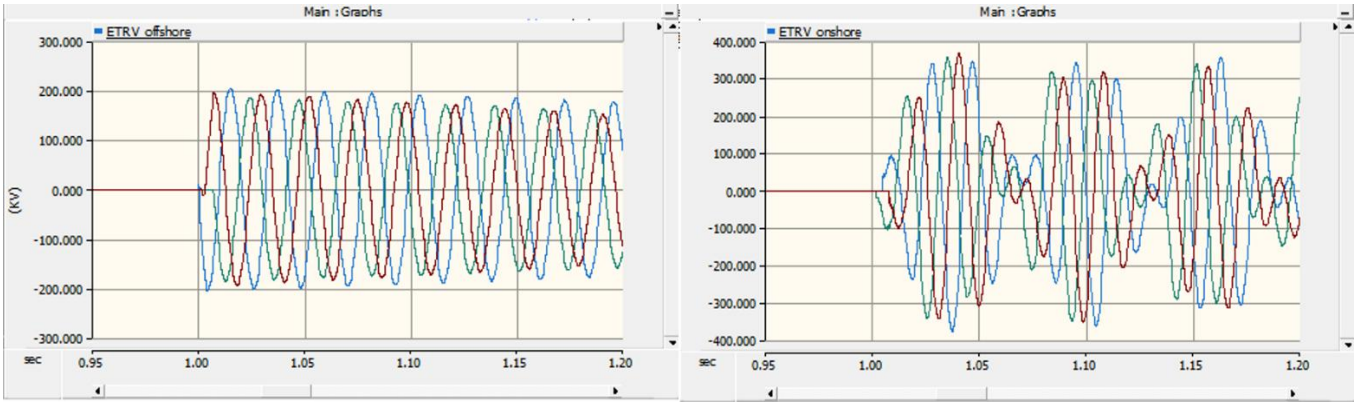


Figure 20: VSR TRV response for offshore SLG fault at 10% loading.

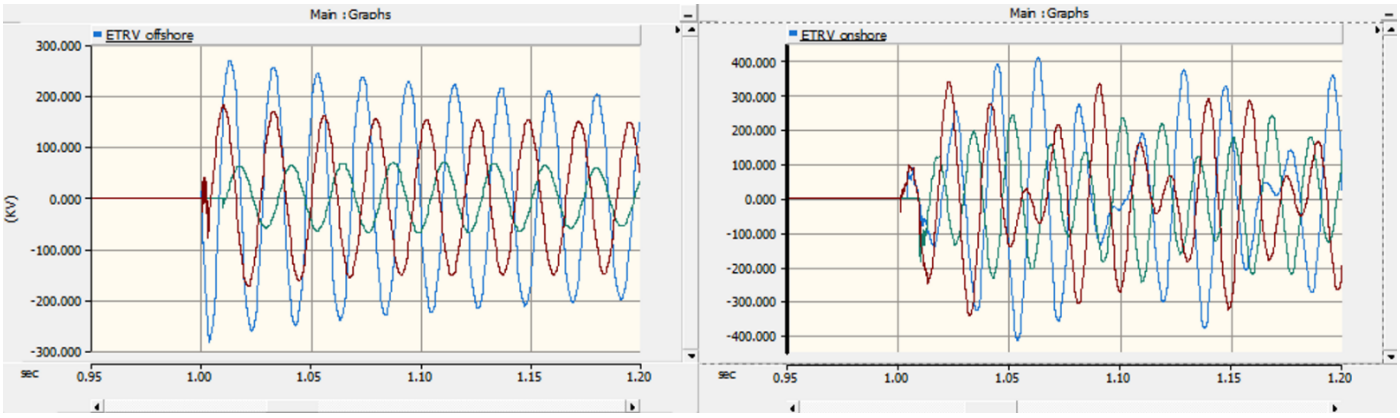


Figure 21: VSR TRV response for offshore LLG fault at 10% loading.

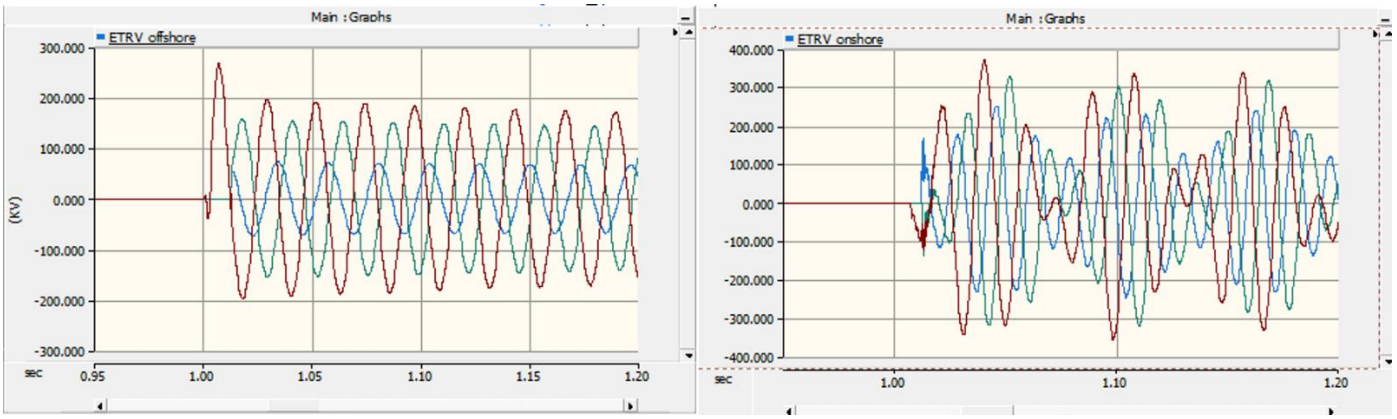


Figure 22: VSR TRV response for offshore LL fault at 10% loading.

For the VSR configuration at 100% loading, the highest offshore TRV is 343 kV for the line-to-line fault, while the highest onshore TRV is 464 kV for the three-phase fault as shown in figures 23, 24, 25 and 26. These values also remain below the breaker capability limits.

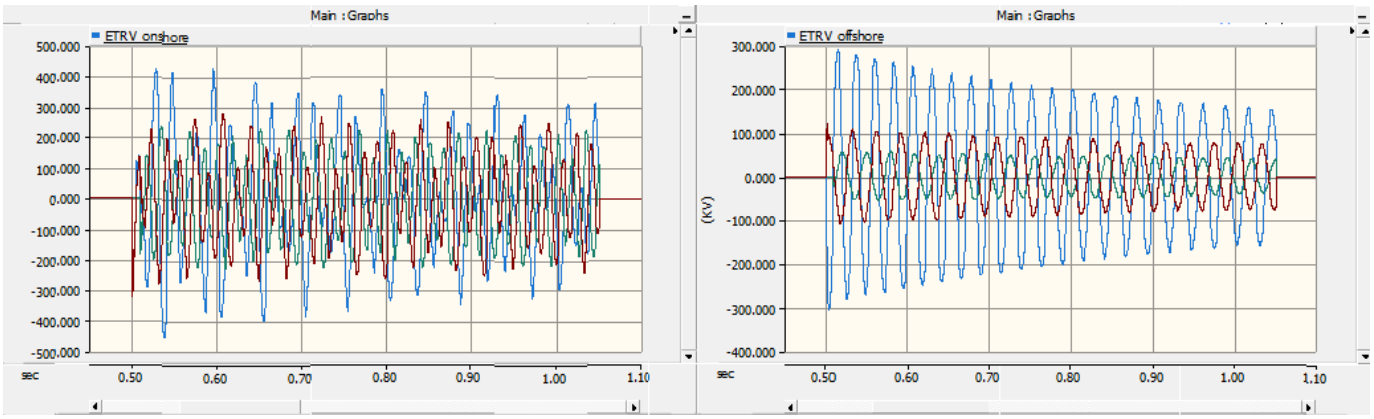


Figure 23: VSR TRV response for offshore 3ph fault at 100% loading.

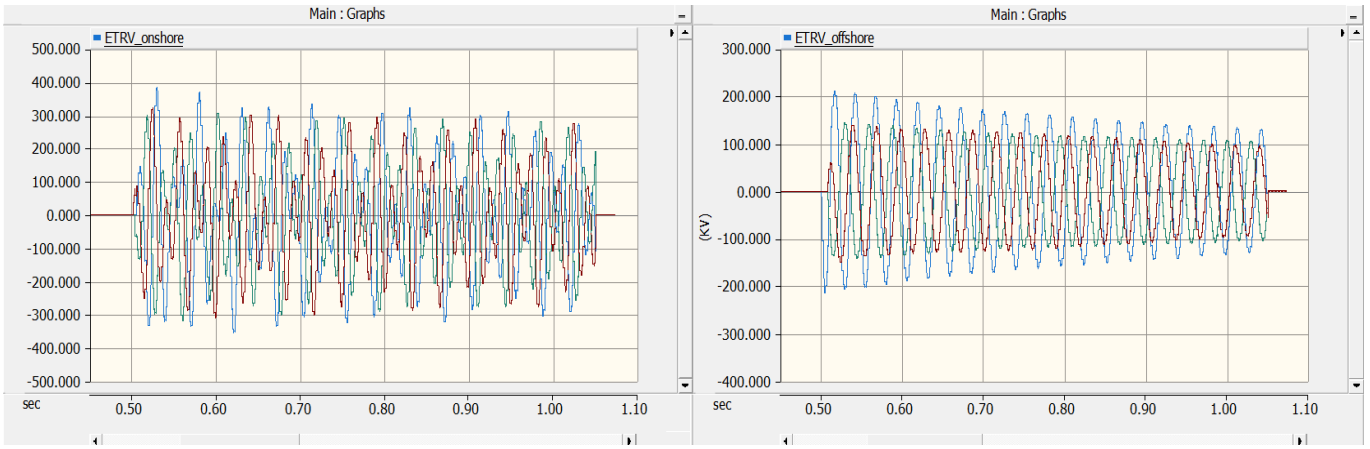


Figure 24: VSR TRV response for offshore SLG fault at 100% loading.

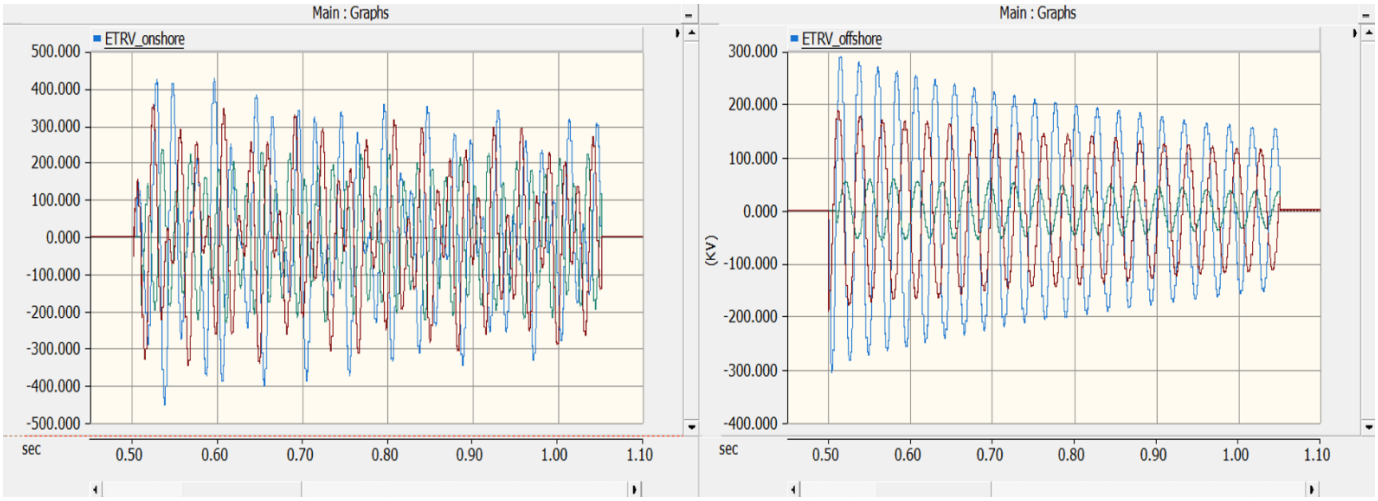


Figure 25: VSR TRV response for offshore LLG fault at 100% loading.

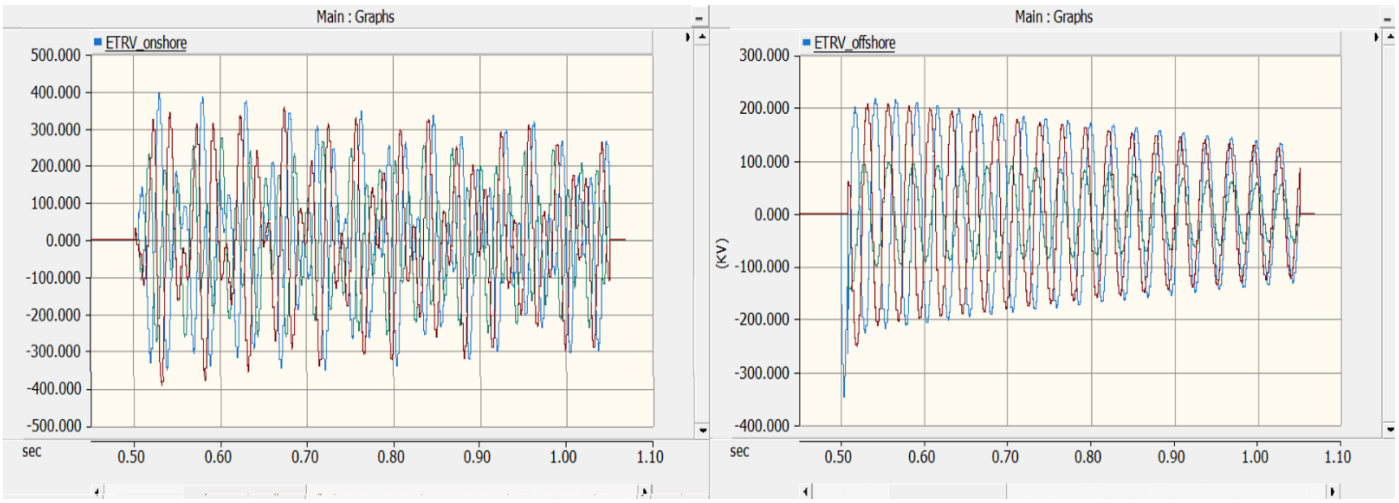


Figure 26: VSR TRV response for offshore LL fault at 100% loading.

Table 8: VSR TRV results

Loading	Fault type	Offshore TRV peak	Offshore limit	Onshore TRV peak	Onshore limit
10%	3PH	282 kV	472 kV	414 kV	562 kV
10%	SLG	204 kV	472 kV	378 kV	562 kV
10%	LLG	281 kV	472 kV	408 kV	562 kV
10%	LL	268 kV	472 kV	363 kV	562 kV
100%	3PH	306 kV	472 kV	464 kV	562 kV
100%	SLG	210 kV	472 kV	388 kV	562 kV
100%	LLG	303 kV	472 kV	451 kV	562 kV
100%	LL	343 kV	472 kV	379 kV	562 kV

For the STATCOM configuration at 10% loading, the highest offshore TRV is 366 kV for the three-phase fault, while the highest onshore TRV is 435 kV, also for the three-phase fault as shown in figures 27, 28, 29 and 30. Both values are below the breaker capability limits.

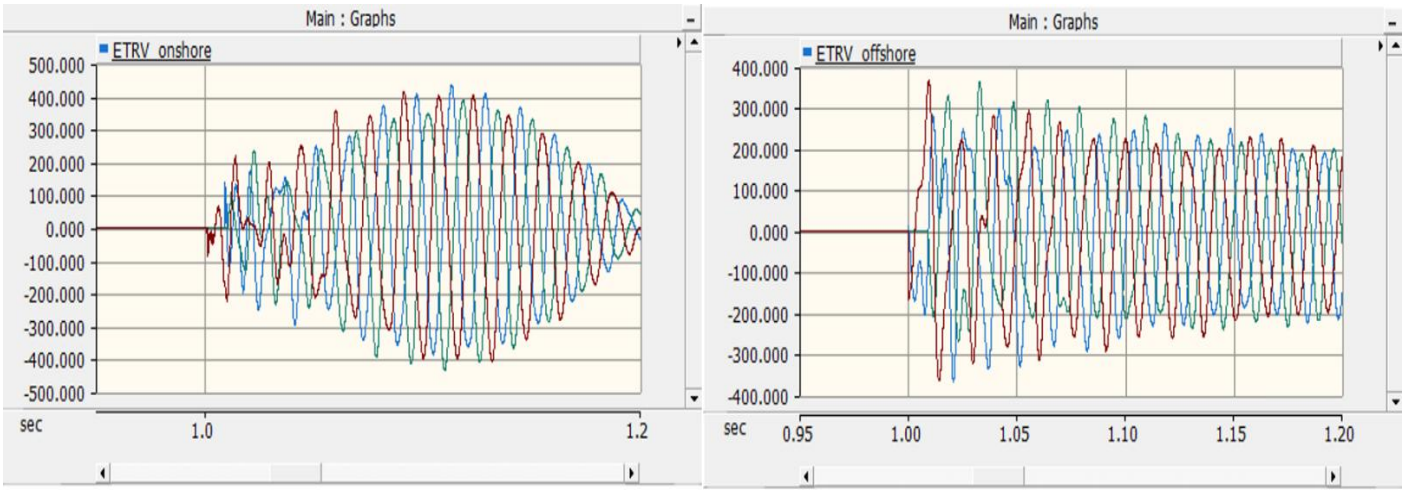


Figure 27: STATCOM TRV response for offshore 3ph fault at 10% loading.

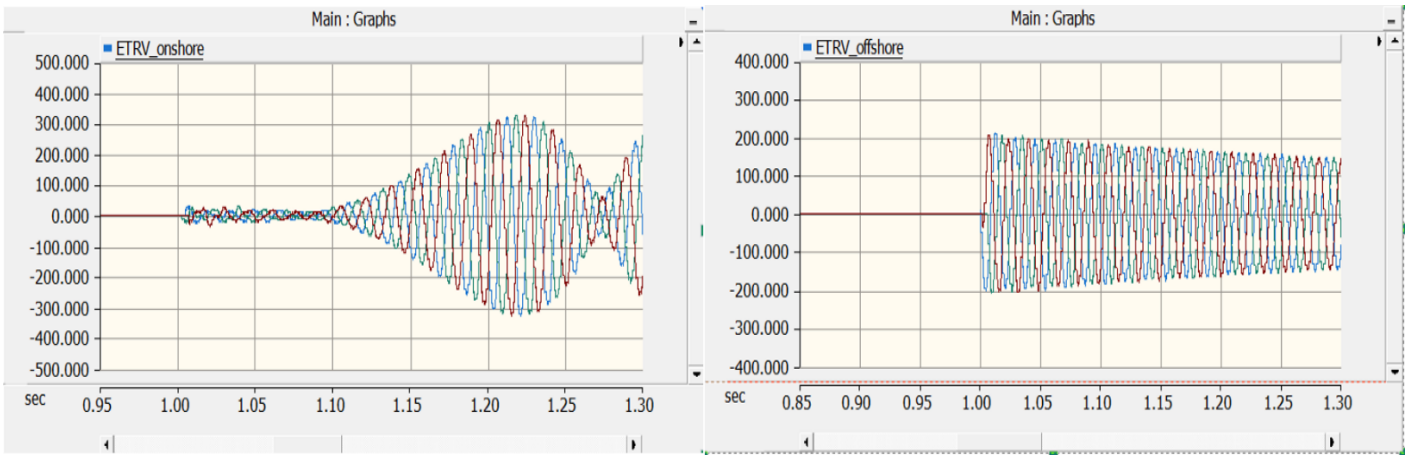


Figure 28: STATCOM TRV response for offshore SLG fault at 10% loading.

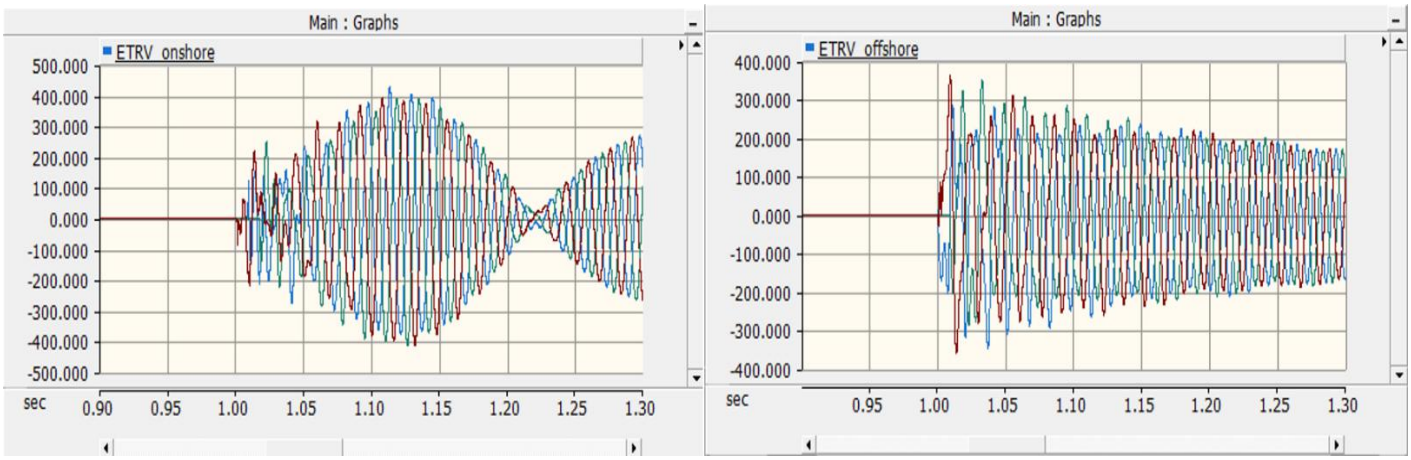


Figure 29: STATCOM TRV response for offshore LLG fault at 10% loading.

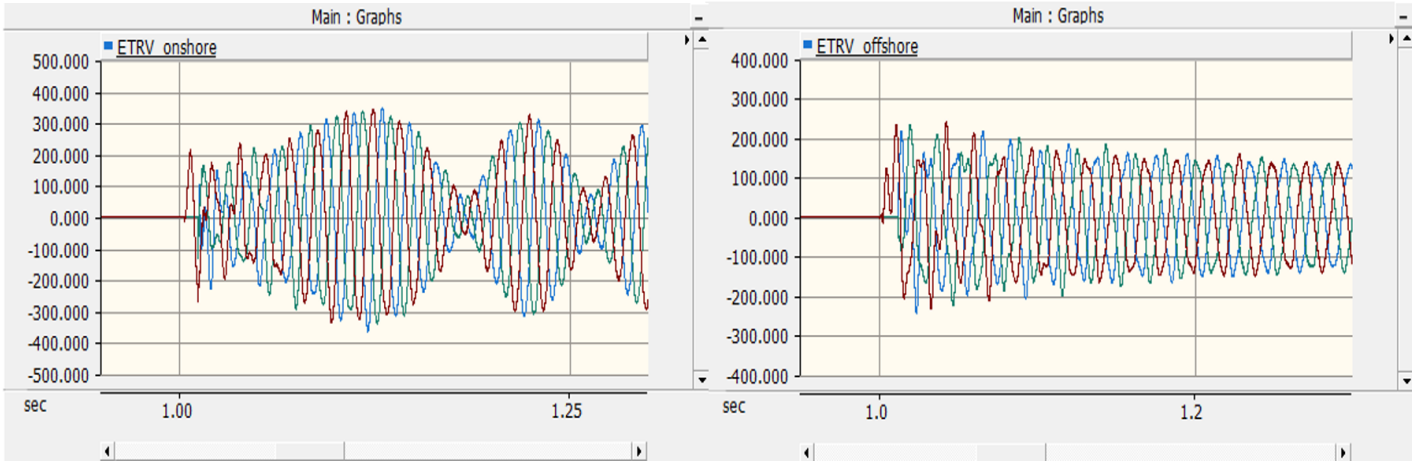


Figure 30: STATCOM TRV response for offshore LL fault at 10% loading.

For the STATCOM configuration at 100% loading, the highest offshore TRV is 412 kV for the three-phase fault, while the highest onshore TRV is 437 kV for the line to line to ground fault as shown in figures 31, 32, 33, and 34. These values also remain below the specified breaker limits.

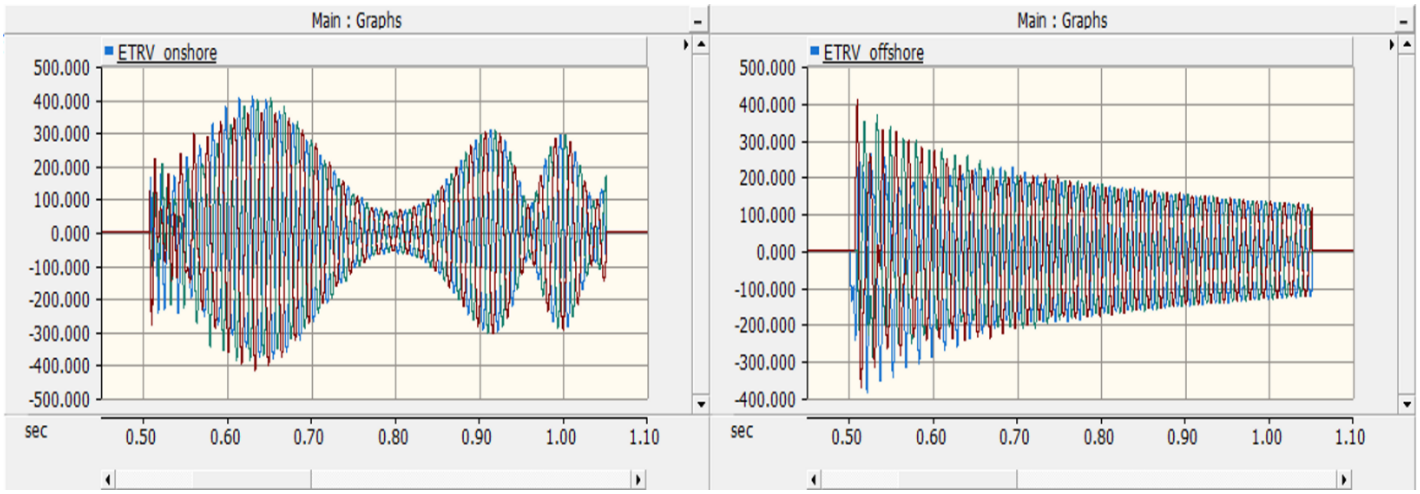


Figure 31: STATCOM TRV response for offshore 3ph fault at 100% loading.

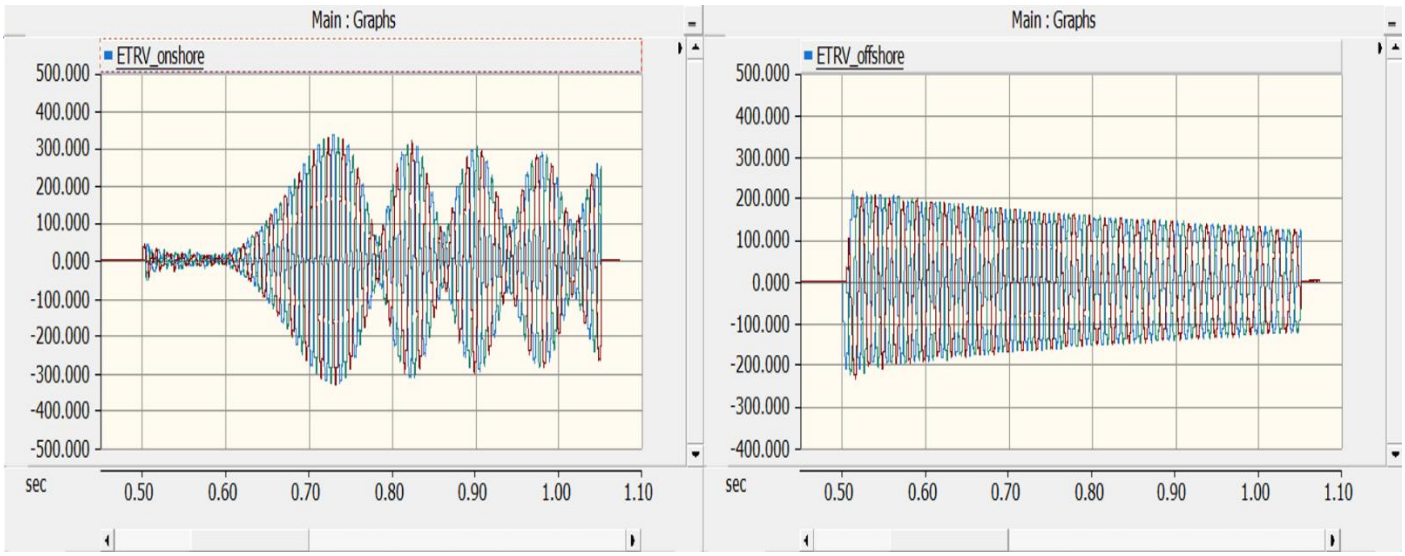


Figure 32: STATCOM TRV response for offshore SLG fault at 100% loading.

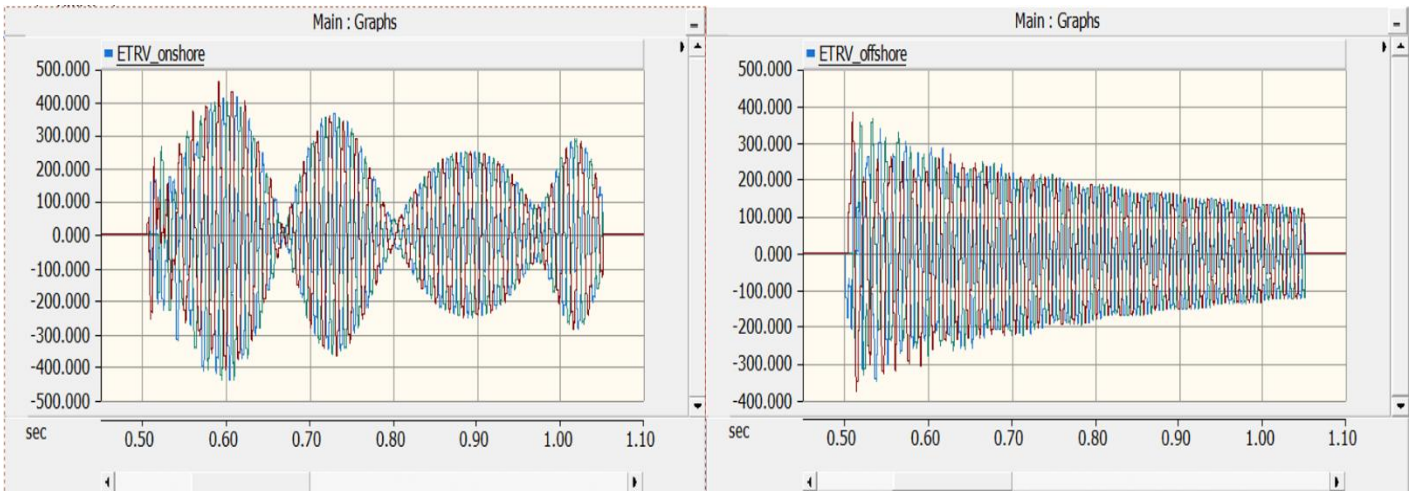


Figure 33: STATCOM TRV response for offshore LLG fault at 100% loading.

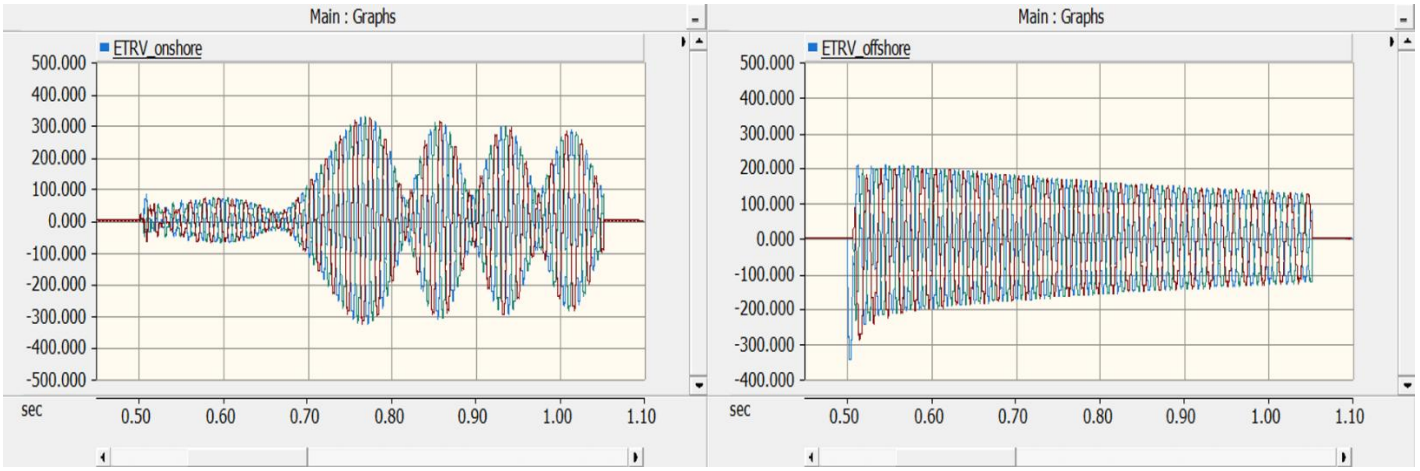


Figure 34: STATCOM TRV response for offshore LL fault at 100% loading.

Table 9: STATCOM TRV results

Loading	Fault type	Offshore TRV peak	Offshore limit	Onshore TRV peak	Onshore limit
10%	3PH	366 kV	472 kV	435 kV	562 kV
10%	SLG	212 kV	472 kV	326 kV	562 kV
10%	LLG	350 kV	472 kV	414 kV	562 kV
10%	LL	242 kV	472 kV	362 kV	562 kV
100%	3PH	412 kV	472 kV	414 kV	562 kV
100%	SLG	227 kV	472 kV	323 kV	562 kV
100%	LLG	366 kV	472 kV	437 kV	562 kV
100%	LL	316 kV	472 kV	304 kV	562 kV

The TRV results show that both VSR and STATCOM configurations satisfy the breaker capability criterion for all simulated fault types and loading conditions. The STATCOM case gives higher offshore TRV values in some cases, especially for three phase faults, while the VSR case gives the highest onshore TRV value during the 100% loading three phase fault. However, none of these cases exceeds the specified breaker capability limits.

4.4 Disturbance and Tap Change Response

The disturbance response assessment considered two operating scenarios: sudden load loss and VSR tap-changing operation. In the VSR case shown in figure 35, tap changing was simulated by temporarily connecting a small parallel reactor to the onshore reactor, with the switching event occurring at approximately 0.5 s. This operation produced a short-duration voltage spike lasting only a few milliseconds, after which the voltage quickly returned to within the acceptable operating range. A sudden load loss of approximately 20 MVA was then introduced at around 1.0 s. Following the disturbance, the system voltage remained stable and within acceptable limits.

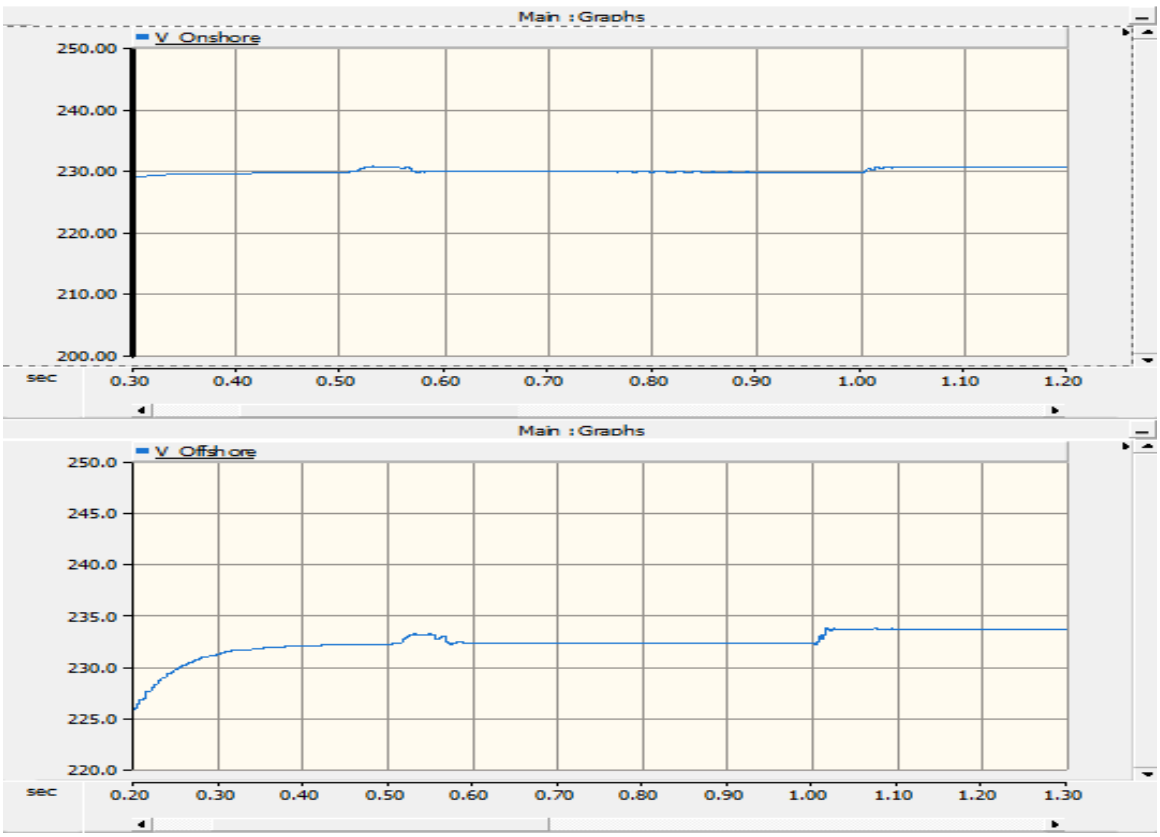


Figure 35: VSR voltage response during tap change operation and sudden 20 MVA load loss.

For the STATCOM case shown in figure 36, an approximately 20 MVA load loss occurs around 0.5 s. The voltage remains controlled after the load reduction, with no sustained overvoltage observed in the result. Compared with the VSR case, the STATCOM response does not involve discrete tap movement, so the voltage response is smoother.

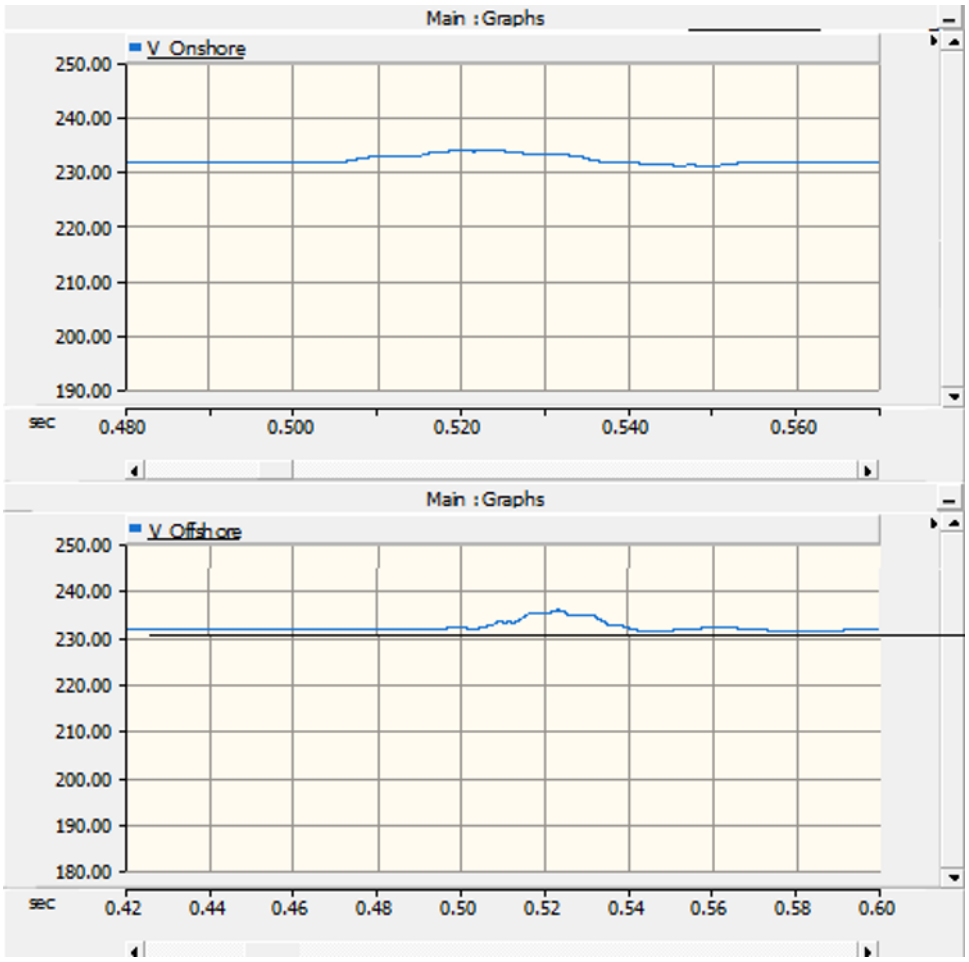


Figure 36: STATCOM voltage response during sudden 20 MVA load loss.

The VSR result shows that voltage regulation is achieved through discrete tap changing action. When the tap position changes, the compensation level changes in steps. In the simulated case, the voltage disturbance caused by the tap-changing operation is of short duration and remains within the acceptable operating range. After the sudden load loss, the VSR-compensated system also maintains acceptable voltage behavior. In comparison, the STATCOM response is smoother because its reactive-power output is controlled electronically rather than through mechanical tap steps. The STATCOM waveform shows a more continuous voltage response after the load change, with no visible step-type disturbance. Therefore, both technologies maintain acceptable voltage performance after the sudden load change, but the STATCOM provides a smoother dynamic response, while the VSR response reflects the discrete nature of tap-changing compensation.

4.5 Summary of Technical Findings

The uncompensated system experiences excessive voltage rise, reaching approximately 1.15 p.u. near the receiving end. This confirms the need for reactive power compensation in the long HVAC submarine cable system studied. Both VSR and STATCOM compensation reduce the voltage profile to within the required 0.95–1.05 p.u. operating range under 10% and 100% loading.

The zero sequence frequency scan results show that the VSR and STATCOM configurations produce different resonance characteristics. The VSR case has its dominant impedance peak at a lower frequency, while the STATCOM case shifts the dominant peak to approximately 156–157 Hz and produces a higher offshore impedance peak. The TRV results show that all simulated cases remain below the specified breaker capability limits. Finally, the disturbance response results show that both technologies maintain acceptable voltage behavior following a sudden 20 MVA load loss, while the VSR case also demonstrates acceptable voltage behavior during tap change operation.

Overall, both compensation technologies are technically feasible for the studied system. The VSR configuration provides acceptable voltage control using the industrial reactor arrangement, while the STATCOM configuration provides faster controllable shunt support and a slightly flatter full load voltage profile. These technical findings provide the basis for life cycle cost assessment in Chapter 5.

Chapter 5
life Cycle Cost Assessment

This chapter presents a life cycle cost comparison of the VSR and STATCOM compensation alternatives. The objective is to compare the total cost of ownership of the two solutions based on the technical configurations evaluated in Chapter 4. The comparison assumes a greenfield development, in which both the VSR and STATCOM alternatives are considered newly installed systems. The assessment includes the initial capital cost, the present value of energy losses, and the present value of annual operation and maintenance (O&M) costs over a 20-year study period.

5.1 Life Cycle Cost Method

The life cycle cost method follows the general structure of the equipment life cycle cost industrial practice used in international oil and gas companies [21]. The procedure defines life cycle cost over a 20-year period and includes both procurement cost and operating cost as:

$$[LCC = IC + OC] \quad 15$$

where IC is the initial cost and OC is the present value of operating power cost. In this thesis, the same approach is adapted for reactive power compensation equipment by treating the active power losses of the compensation devices as the operating power term. The same procedure is used to estimate the operating cost based on the required operating power, electricity cost, annual operating hours, operating factor, and present value factor.

For this study, the life cycle cost is calculated as:

$$[LCC = CAPEX + PV_{loss} + PV_O\&M] \quad 16$$

where CAPEX is the installed capital cost, PV_loss is the present value of energy loss cost, and PV_O&M is the present value of annual operation and maintenance cost. The present value factor is calculated as:

$$\left[PV = \frac{[(1 + i)^{n} - 1]}{[i(1 + i)^{n}]}\right] \quad (17)$$

where i is the annual discount rate and n is the study period in years. Using a discount rate of 2.3% and a study period of 20 years, the present value factor is approximately 15.89.

5.2 Cost Assumptions

The cost comparison is based on 2023 U.S. installed-cost estimates obtained from the project design documentation [22]. The fixed reactor cost is $15,349/MVAr. Since the evaluated reactor alternative is a variable shunt reactor, an additional 50% is added for the tap changer. Therefore, the VSR installed cost basis becomes:

VSR unit cost = 15,349 × 1.5 = 23,023.5 $/MVAr

The STATCOM installed cost base is $215,250/MVAr at 230 kV. Therefore, the assessment uses the 2023 U.S. procurement cost values directly.

Table 10: Main economic assumptions

Parameter	**VSR**	**STATCOM**
Configuration	6 × 123 MVAr	4 × 150 MVAr
Total installed rating	738 MVAr	600 MVAr
Base installed unit cost	$23,023.5/MVAr	$215,250/MVAr
Inflation factor	Not applied	Not applied
Delivery/transportation factor	Not applied	Not applied
Active loss assumption	0.3% of rating	1.5% of rating
Annual O&M cost	1.2% of CAPEX	1.45% of CAPEX
Energy cost	$0.10/kWh	$0.10/kWh
Annual operating hours	8,760 h/year	8,760 h/year
Study period	20 years	20 years
Discount rate	2.3%	2.3%

Present value factor	15.89	15.89
Project basis	Greenfield	Greenfield

5.3 Capital Cost Comparison

The VSR configuration includes six 123 MVAr units. Therefore, the total installed VSR rating is:

6 × 123 = 738 MVAr

Using the VSR installed cost basis of $23,023.5/MVAr, the total VSR capital cost is:

738 × 23,023.5 = $16.99 million

The STATCOM configuration includes four 150 MVAr units. Therefore, the total installed STATCOM rating is:

4 × 150 = 600 MVAr

Using the STATCOM installed cost basis of $215,250/MVAr, the total STATCOM capital cost is:

600 × 215,250 = $129.15 million

Table 11: Capital cost comparison

Item	VSR	STATCOM
Total installed rating	738 MVAr	600 MVAr
Installed unit cost	$23,023.5/MVAr	$215,250/MVAr
Total CAPEX	$16.99 million	$129.15 million

The STATCOM capital cost is approximately 7.6 times higher than the VSR capital cost. This difference is mainly due to the much higher installed cost per MVAr of STATCOM equipment compared with tap changing shunt reactors.

5.4 Energy Loss and Maintenance Cost

The operating loss cost is calculated from the assumed active losses of each compensation technology. For the VSR case, the loss assumption is 0.3% of installed rating:

VSR losses = 0.003 × 738 = 2.214 MW

For the STATCOM case, the loss assumption is 1.5% of installed rating:

STATCOM losses = 0.015 × 600 = 9.000 MW

Using continuous operation at 8,760 h/year and an energy cost of $0.10/kWh, the annual energy loss cost becomes:

VSR annual loss cost = 2,214 × 8,760 × 0.10 = $1.94 million/year

STATCOM annual loss cost = 9,000 × 8,760 × 0.10 = $7.88 million/year

Applying the present value factor of 15.89, the present value of energy loss cost is approximately $30.81 million for the VSR case and $125.26 million for the STATCOM case.

Annual O&M cost is calculated as a percentage of CAPEX. The VSR annual O&M cost is taken as 1.2% of CAPEX, while the STATCOM annual O&M cost is taken as 1.45% of CAPEX. This gives an annual O&M cost of approximately $0.204 million/year for VSR and $1.873 million/year for STATCOM. The present value of O&M cost is approximately $3.24 million for VSR and $29.75 million for STATCOM.

Table 12: Present value of operating costs

Cost item	VSR	STATCOM
Active loss	2.214 MW	9.000 MW
Annual energy loss cost	$1.94 million/year	$7.88 million/year
Present value of energy losses	$30.81 million	$125.26 million

Annual O&M cost	$0.204 million/year	$1.873 million/year
Present value of O&M	$3.24 million	$29.75 million

5.5 Total Life Cycle Cost Comparison

The total 20-year life cycle cost is obtained by adding CAPEX, present value of energy losses, and present value of O&M cost.

Table 13: Total 20-year life cycle cost comparison

Cost component	VSR	STATCOM
CAPEX	$16.99 million	$129.15 million
Present value of energy losses	$30.81 million	$125.26 million
Present value of O&M	$3.24 million	$29.75 million
Total 20-year LCC	$51.04 million	$284.16 million

The revised results show that the STATCOM alternative has a total 20-year LCC of approximately $284.16 million, compared with approximately $51.04 million for the VSR alternative. Therefore, the STATCOM case is approximately:

284.16 / 51.04 = 5.6 times more expensive than the VSR case over the 20-year study period.

5.6 Discussion

The life cycle cost results show that the VSR solution has a clear cost advantage for the studied system. The VSR configuration has lower capital cost, lower active losses, and lower annual O&M cost. Although the STATCOM configuration provides faster and more flexible reactive power control, this technical advantage does not offset its significantly higher life cycle cost under the assumptions used in this study.

The technical results presented in Chapter 4 demonstrate that both the VSR and STATCOM configurations satisfy the steady-state voltage, transient recovery voltage (TRV), and disturbance-response requirements of the studied offshore HVAC cable system. When the

economic assessment is also considered, however, the VSR emerges as the more cost-effective alternative. The STATCOM remains technically feasible, but its higher cost is difficult to justify unless the project requires additional capabilities beyond those evaluated in this thesis, such as very fast dynamic voltage support or other converter-based ancillary services.

Overall, the results indicate that for the studied long 230 kV offshore HVAC submarine cable system supplying a constant PQ offshore industrial load, the VSR arrangement provides the more attractive life cycle cost solution. The STATCOM alternative improves controllability, but its higher capital cost, higher losses, and higher O&M cost result in a substantially higher 20 year life cycle cost.

Chapter 6
Conclusions and Future Work

This thesis presented a comparative assessment of VSR and STATCOM compensation for a long 230 kV HVAC submarine cable system supplying a constant-PQ offshore industrial load. The comparison was based on an industrial PSCAD model comprising two simultaneously operated submarine cable circuits and was conducted under both 10% and 100% loading conditions. Three system configurations were investigated: an uncompensated baseline, the VSR-compensated configuration, and a modified STATCOM-compensated configuration. The study evaluated the technical performance and life-cycle cost of the two compensation technologies under identical operating conditions to determine their relative suitability for offshore industrial power transmission.

The uncompensated case confirmed the need for reactive power compensation in the studied system. Without compensation, the voltage increased along the submarine cable and reached approximately 1.15 p.u. near the receiving end, exceeding the adopted 1.05 p.u. upper voltage limit. With VSR compensation, the voltage profile was reduced to within the required 0.95–1.05 p.u. range at both 10% and 100% loading. The STATCOM configuration also maintained the voltage within the same acceptable range and produced a slightly flatter voltage profile at full load.

The zero sequence frequency scan results showed that the selected compensation technology affects the resonance behavior of the system. The VSR configuration produced the dominant impedance peak at a lower frequency, while the STATCOM configuration shifted the dominant peak to approximately 156–157 Hz and produced a higher offshore impedance peak. The TRV results showed that all simulated fault cases remained below the specified breaker capability limits for both compensation configurations. The disturbance response results also showed that both technologies maintained acceptable voltage behavior following a sudden 20 MVA load loss, while the VSR tap change case produced only a short and acceptable voltage disturbance.

The life cycle cost assessment showed a clear cost advantage for the VSR solution. Using a 20 year life cycle cost method, the VSR alternative had an estimated total LCC of approximately $51.04 million, while the STATCOM alternative had an estimated total LCC of approximately $284.16 million. Although STATCOM provides faster and more flexible reactive power control, its higher capital cost, higher active losses, and higher O&M cost resulted in a much higher total ownership cost. Therefore, for the studied system and assumptions, the VSR configuration is the more cost-effective solution, while the STATCOM remains technically feasible but economically less attractive.

Future work can extend this study by evaluating additional loading points, different submarine cable lengths, detailed harmonic source interactions, and more detailed STATCOM control strategies. Further work may also include protection coordination studies, detailed switching studies for different operating scenarios, and sensitivity analysis of the economic results using project-specific vendor quotations, loss measurements, energy prices, and discount rates.

Bibliography

[1] O. Efobi, W. Li, M. Das and A. Gole, "Frequency-Dependent Electrical Characteristics of Submarine Cables in Low Frequency High Voltage ac (LF-HVac) Transmission for Offshore Wind," in *2023 IEEE Power & Energy Society General Meeting (PESGM)*, Orlando, 2023.

[2] CIGRE WG B1.27 report 490, "Recommendations for testing of long AC submarine cables with extruded insulation for system voltage above 30 (36) to 500 (550) kV," CIGRE, Paris, 2012.

[3] CIGRE WG B1.47 report 680, "IMPLEMENTATION OF LONG AC HV AND EHV CABLE SYSTEMS," CIGRE, Paris, 2017.

[4] J. Song-Manguelle, T. M. Harfman, S. Chi, S. K. Gunturi and R. Datta, "Power transfer capability of HVAC cables for subsea transmission and distribution systems," in *Industry Applications Society 60th Annual Petroleum and Chemical Industry Conference*, Chicago, 2013.

[5] A. Al-Abdulwahab, R. El-Mahayni, J. Thomai and K. Ai-Qahtani, "Challenges in Offshore Power Systems: Pushing HVAC Transmission to the Limit," in *2023 IEEE IAS Petroleum and Chemical Industry Technical Conference (PCIC)*, New Orleans, 2023.

[6] T. Treider and A. Holdyk, "Long HVAC Subsea Cable Connections: Review of Technical Challenges and Research Needs," in *EERA DeepWind Conference*, Trondheim, 2025.

[7] S. Lauria, M. Schembari, F. Palone and M. Maccioni, "Very long distance connection of gigawatt-size offshore wind farms: extra high-voltage AC versus high-voltage DC cost comparison," *IET Renewable Power Generation,* vol. 10, no. 5, pp. 713-720, 2016.

[8] P. Marini, "Shunt Reactor Compensation for Subsea Cables in Industrial Plants," in *2023 PCIC Energy Europe (PCIC Energy)*, Milan, 2023.

[9] G. Liu, M. Fan, P. Wang and M. Zheng, "Study on Reactive Power Compensation Strategies for Long Distance Submarine Cables Considering Electrothermal Coordination," *Journal of Marine Science and Engineering,* vol. 9, no. 1, 2021.

[10] S.-H. Song and S.-B. Kim, "Coordinated Reactive Power Control with a Variable Shunt Reactor and an Inverter-Based Wind Power Plant," *Energies,* vol. 15, no. 13, 2022.

[11] D. Wu, G.-S. Seo, L. Xu, C. Su, L. Kocewiak and Y. Sun, "Grid Integration of Offshore Wind Power: Standards, Control, Power Quality and Transmission," *IEEE Open Journal of Power Electronics,* vol. 5, pp. 583 - 604, 2024.

[12] IEEE Std 1052-2018, "IEEE Guide for Specification of Transmission Static Synchronous Compensator (STATCOM) Systems," IEEE, 2018.

[13] A. R. Khatib, S. A. Al-Ghamdi, P. S. V. Kumar and T. G. Paul, "Variable Shunt Reactor Control for Voltage Compensation for Submarine Cable at Offshore Facility," in *IEEE IAS Petroleum and Chemical Industry Technical Conference (PCIC)*, New Orleans, 2023.

[14] A. Župan, B. Filipović-Grčić and D. Filipović-Grčić, "Transients caused by switching of 420 kV three-phase variable shunt reactor," *Electric Power Systems Research,* vol. 138, pp. 50-57, 2016.

[15] A. Z. Hussein, N. H. Saad and S. F. Mekamer, "Reactive Power and Voltage Control of Offshore Wind Parks Based PI Controller Tuning for STATCOM via Genetic Algorithm," in *2018 Twentieth International Middle East Power Systems Conference (MEPCON)*, Cairo, 2018.

[16] A. Narula, P. Imgart, M. Bongiorno and M. Beza, "Empowering offshore wind with ES-STATCOM for stability margin improvement and provision of grid-forming capabilities," *Electric Power Systems Research,* vol. 234, 2024.

[17] PSCAD, "Overhead Lines and Cable Modeling Guidelines for PSCAD," PSCAD, 2023.

[18] CIGRE WB B5.37 report 546, "Protection, Monitoring and Control of Shunt Reactors, Technical Brochure 546," CIGRE, Paris, 2013.

[19] IEEE Std 3002-2018, "IEEE Recommended Practice for Conducting Harmonic Studies and Analysis of Industrial and Commercial Power Systems," IEEE, 2018.

[20] Cigre WG A3.11 report 305, "Guide for Application of IEC 62271-100 and IEC 62271-1, Part 2: Making and Breaking Tests," Cigre, Paris, 2006.

[21] SA SAEP-341, "Equipment Life Cycle Cost Procedure," 2016.

[22] A. Altamimi, Interviewee, *Designer engineer.* [Interview]. 13 June 2026.