Enhancing Voltage Profile and Stability of the North-South 400kV Transmission Interconnection in Oman using STATCOM Technology

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ABSTRACT

The research paper investigates the performance enhancement of the 400kV transmission interconnection connecting the northern and southern regions of the Sultanate of Oman through the implementation of a Static Synchronous Compensator (STATCOM). This interconnection project holds significant promise in facilitating efficient power exchange, promoting renewable energy integration, and supporting the Gulf Cooperation Council (GCC) power connection. However, the integration of these grids poses challenges to voltage security, quality, and reliability. The study employs DIgSILENT PowerFactory software to model and simulate the 667km transmission line, comprising five key grid stations. The transmission line analysis under varying load scenarios reveals potential voltage profile deterioration, particularly in scenarios involving increased energy demand and interconnection to the Petroleum Development of Oman Company (PDO) network. To address these challenges, a suitable STATCOM design is proposed. The paper navigates the stages of model development, simulation, STATCOM design, and optimal placement through a comprehensive methodology. The proposed three-phase, three-wire STATCOM configuration is designed with carefully determined component ratings, ensuring effective reactive power compensation and voltage enhancement. Simulation results showcase the optimal placement of the STATCOM at the Duqm 400kV bus, offering improved voltage profiles and stability across the interconnected system. This research provides crucial insights for power system planners and engineers, facilitating informed decision-making regarding the deployment of STATCOM technology to bolster the performance and reliability of the 400kV transmission interconnection in Oman. As the nation pursues ambitious economic and infrastructure development goals outlined in Oman Vision 2040, the findings of this study are poised to contribute significantly to the achievement of a robust and resilient power infrastructure.

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1. INTRODUCTION

The power sector in the Sultanate of Oman is divided into different regional grids. The interconnection of two major power grids in the north and south regions of the sultanate through 400 kV will result in many advantages such as reduction in spinning reserves and efficient power exchange. In addition, it will be capable of providing renewable energy sources penetration and promoting the Gulf Cooperation Council (GCC) power connection[1][2]. However, such interconnection will pose several challenges in terms of voltage security, quality, and reliability. The Sultanate of Oman has also witnessed a great development in the size of the economy and infrastructure, and the interest in diversifying sources of income, which coincides with the emergence of many diverse projects throughout the country, according to the vision of Oman 2040. Therefore, all this was accompanied by continuous growth in the electricity demand. From this point of view, the project to connect the electricity between the main electricity network in the north of Oman with the network of the Petroleum Development of Oman Company (PDO) and the electricity network in the central region, and the network of Dhofar Governorate in the south through a 400-kV transmission line is a project to build the backbone of the electricity network in the Sultanate of Oman [3].

This paper focuses on the study and analysis of the 400kV transmission interconnection performance and identifying the system demand point that requires the implementation of a STATCOM controller to enhance its voltage profile and stability. In addition, the paper also provides the design and optimal placement of STATCOM in the interconnecting grid stations of the north and south of Oman's power system networks.

2. SYSTEM DESCRIPTION

At voltages of 132 kV and above, the Oman Electricity Transmission Company (OETC) is permitted to carry out all regulated activities of electricity transmission and dispatch across the Sultanate of Oman. While Dhofar (the southern portion of Oman) only has one operating voltage, 132 kV, the transmission system in northern Oman currently supports three operating voltages: 400 kV, 220 kV, and 132 kV. The current transmission network connects large energy users and producers in the governorates of Muscat, Batinah South, Batinah North, Dhahirah, Buraimi, Dakhliyah, Sharquiya South, Sharquiya North, and Wusta over the entirety of Oman's north. A single circuit overhead line between Nizwa on the OETC system and Nahadah on the PDO system connects the OETC transmission system at the main interconnected system (MITS) with the PDO transmission network at 132 kV. Power transfer across the interconnection is anticipated to be negligible under normal circumstances, but in the event of an emergency on either network, the interconnection can enable a power transfer to compensate for the difference. The PDO System is integrated through the 400 kV transmission system which is energized in the second quarter of 2023. Additionally, a single circuit overhead line connects the Dhofar Wind Farm at the OETC transmission system and Harweel at the PDO transmission system to the 132 kV PDO transmission network [1].

OETC adopted a 400kV transmission line interconnection between the main interconnected system in the north PDO system, the Dhofar transmission system, and the remote area of Duqm. According to the feasibility assessment, the interconnection project has a positive economic Net Present Value (NPV). Fuel savings resulting from greater dispatch coordination between the power systems, access to regions with potential for renewable energy, sharing of spinning re-serves (cutting operational costs), and increased grid security and availability are among the predicted benefits. The PDO, Duqm, and Mahout systems will be connected more efficiently due to the new 400 kV interconnection project. In order to replace the diesel generators in the Duqm and Mahout areas by the second quarter of 2023, the project will be carried out by building the Barik, Suwaihat, Duqm, and Mahout grid stations with associated 400 kV OHL. The starting connection point of the 400kV transmission line which is the Nahadah 400/132kV grid station is completed in the second quarter of 2022.

According to OETC load flow analyses, the proposed 400 kV, 220 kV, and 132 kV transmission developments will significantly increase the transmission system's capacity, allowing it to handle increased demand while still adhering to the Transmission Security Standard. In addition, the economic assessment of OETC assumes that renewable energy development will result in renewable energy source capacity totaling 400 MW by 2020 and up to 4000 MW by 2030.[1] As a result, where there is extra capacity, there should be apertures for connecting new loads.

The 400kV transmission line connecting the north and south of Oman has been implemented using DIgSILENT Power Factory software. The total length of the transmission line is 667km connecting 5 power grid stations: Nahadah, Barik, Suwaihat, Duqm, and Mahout as shown in table 1.

Table 1. Grid stations of 400kV transmission system

No.	Grid station	Voltage level	Transformers capacity
1	Nahadah	400/132kV	2x500MVA
2	Barik	400/132kV	2x500MVA
3	Suwaihat	400/132kV	2x500MVA
4	Duqm	400/132/33kV	2x500MVA
5	Mahout	400/33kV	2x125MVA

Table 2 illustrates the 400kV transmission line parameters. The transmission line conductor type is Quad YEW AAAC (All Aluminum Alloy Conductors).

Table 2. The parameters of the 400kV transmission line

From Grid Station	To Grid Station	Voltage kV	No. Circuits	Conductor Type OHL	Length km	R(Ω/km)	X(Ω/km)	B(MS/km)	Rating MVA
Mahout	Duqm	400	2	Quad YEW	152	0.021091	0.257782	5.18	1774
Duqm	Suwaihat	400	2	Quad YEW	191	0.021091	0.257782	5.18	1774
Suwaihat	Barik	400	2	Quad YEW	129	0.021091	0.257782	5.18	1774
Barik	Nahadah	400	2	Quad YEW	195	0.021091	0.257782	5.18	1774

It’s an aluminum, magnesium, and silicon heat-treated alloy. These materials are valued for their high tensile strength, lightweight, and corrosion resistance. The thermal rating of the modeled 400kV transmission is 1774 MVA[1].
The implemented 400kV transmission line has been simulated with the actual load demand of the Mahout grid station (21.3MW, 7Mvar) and Duqm grid station (79.6MW, 26.2Mvar). In addition, according to the actual operation condition, the load exchange between the petroleum development of Oman company and OETC is set to be zero at Nahadah, Barik, and Suwaihat grid stations. As shown in table 3 the results of the line-to-line voltage of the 400KV buses of all grid stations (Nahadah, Barik, Suwaihat, Mahout, Duqm) are within the allowable operation limits according to OETC standards for 400 kV voltage level (±2.5%).

Table 3. 400kV Grid Stations Bus Voltages

Grid Station		Nahadah	Barik	Suwaihat	Duqm		Mahout
Base Model	Bus Voltage (L-L) kV	400	397.1	395.2		392.5	392.1

However, the power demand market expansion is possible shortly due to the government's Vision 2040 development strategy to increase tourism, modernize agriculture, establish free industrial zones, promote technology, and create a start-up ecosystem. From this point of view, this research paper depends on the increase in energy demand in the future, and then the increase in energy demand can lead to the emergence of problems in the 400kV transmission line connecting the north and south of Oman such as the drop in the voltage profile of the 400 kV buses. Therefore, STATCOM can be an optimal solution for the enhancement of the voltage profile in the 400 kV buses. In the subsequent sections, different load scenarios will be encountered to indicate the critical value of the load that can be supplied by the 400kV transmission line. In addition, the design and implementation of STATCOM will be discussed as a compensation technique to enhance the voltage profile. Moreover, placement optimization of STATCOM will be indicated to find the optimal location of the STATCOM in the 400kV transmission line under the study.

3. METHODOLOGY

The flow chart shown in Figure 1 illustrates the methodology adopted.

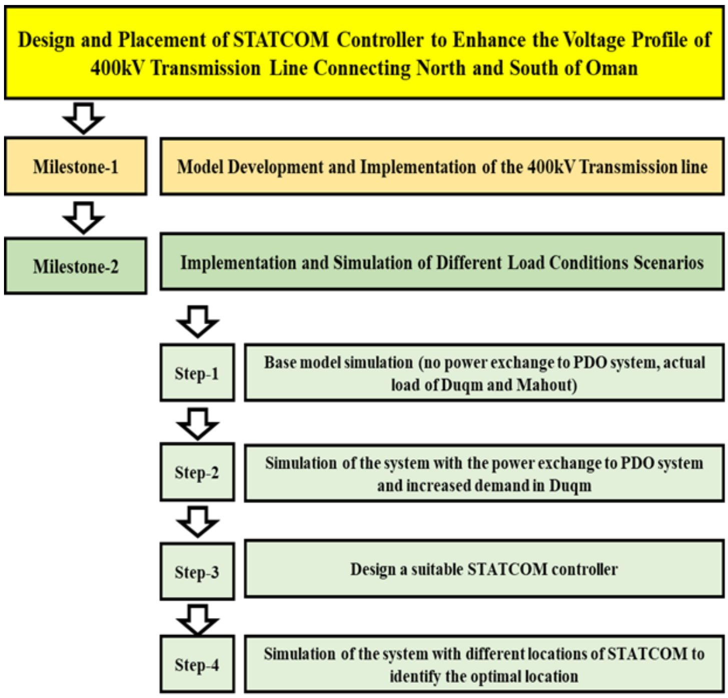

Figure. 1. Methodology Flowchart.

The adapted methodology has been divided into two main milestones to reach the required efficient findings and results. The first milestone includes the model development and implementation of the 400kV transmission line system under the study with the identification of the actual system parameters and the normal operation demands. The second milestone includes the simulation of the studied model to be compared with several load conditions operation scenarios to indicate the size of the demand that affects the voltage profile of the studied 400kV transmission line. Thereby, a recommended suitable STATCOM design is added to enhance the voltage profile of the transmission line. Finally, several scenarios of the designed STATCOM location are considered to finalize the optimal placement of the SATCOM in the studied 400kV transmission line

4. SYSTEM MODEL & SIMULATION

The studied 400kV transmission line system connecting north and south of Oman is modeled, implemented, and simulated using DIgSILENT PowerFactory software. In the following sections, different load operation scenarios are compared to the normal load operation to indicate the change in the voltage profile of the system accompanied by the load raise. The description of the simulation scenario's load operation conditions is illustrated in Figure 2.

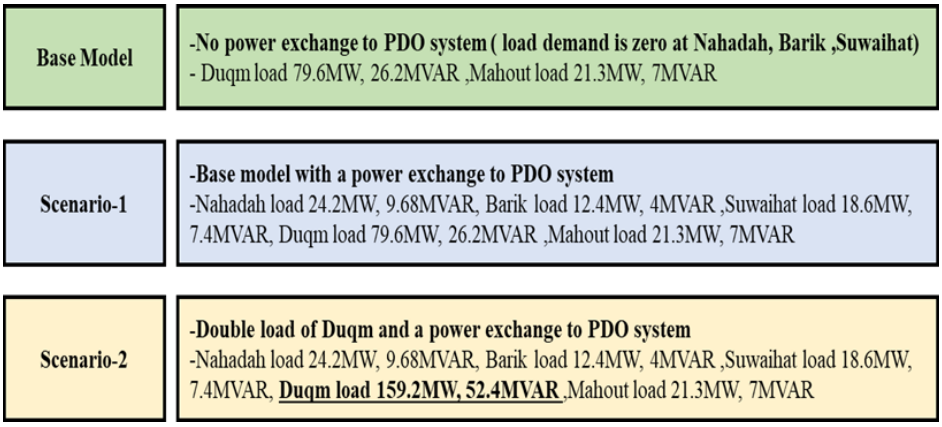

Figure. 2. Power demand data of the base model and the system-modeled scenarios.

The normal operating condition with the actual load demand of the 400kV transmission line has been considered as a base model to be compared with different load operation scenarios. The power exchange between the PDO power system and the 400kV transmission line is set to be zero according to the actual operation between the OETC power system and the PDO power network. Hence, the load demands in Nahadah, Barik, and Suwaihat grid stations are equal to zero in the base system simulation model. However, the total load demand in the Duqm grid station is 79.6MW and 26.2MVAR. The total load demand in the Mahout grid station is 21.3MW and 7MVAR. The load flow simulation of the base model has been conducted using DIgSILENT PowerFactory which indicates that the voltages in the 400kV grid station buses are within the allowable operation limits (±2.5%). The lowest voltage value of the 400kV bus is shown in the Mahout grid station with only a 1.975% voltage drop. In simulation scenario-1, the power exchange between the PDO power system through Nahadah, Barik, and Suwaihat grid stations takes place. The active power demand is 24.2MW,12.4MW and 18.6MW for Nahadah, Barik, and Suwaihat respectively. The reactive power demand is 9.68MVAR, 4MVAR, and 7.4MVAR for Nahadah, Barik, and Suwaihat respectively. In addition, the load demand in Duqm and Mahout is considered to be the same as the load demand of the base model. In this case, the voltage values at the 400kV bus indicate that all the voltage profiles of the grid stations are within the allowable operation limits. However, it can be noticed that the voltage value at Mahout 400kV bus is 390.7kV which is close to the unacceptable operation limit which should be between 390kV and 410kV. In simulation scenario-2, the load demand of the Duqm grid station has been considered to be double compared to the base model. The power demand in Duqm is expected to be increased due to the great attention that has been directed by the government of Oman to invest in big projects. In addition, the strategic location of Duqm attracts international companies to invest in different sectors such as renewable energy, oil, gas, logistics, and marine services. Hence in this case the load demand of the Duqm grid station is considered to be 159MW and 52.4MVAR. PDO power demand has been also considered in Nahadah, Barik, and Suwaihat grid stations. The load flow of simulation scenario-2 illustrates the voltage values at 400kV busses of Suwaihat, Duqm, and Mahout grid stations are beyond the allowable operation limits. The voltage drop exceeds the minimum allowable value of 390kV and Mahout grid station has the maximum voltage drop with a percentage of 4.057%. In addition, the transmission lines total loss result indicates that the reactive power loss exceeds 2MVAR in each transmission line. These results highlight that implementation of a suitable designed STATCOM is required for reactive power compensation and enhancing the voltage profile of the transmission line system. Figure 3 shows the voltage magnitude at 400 kV buses of the base model, simulation scenario-1, and simulation scenario-2.

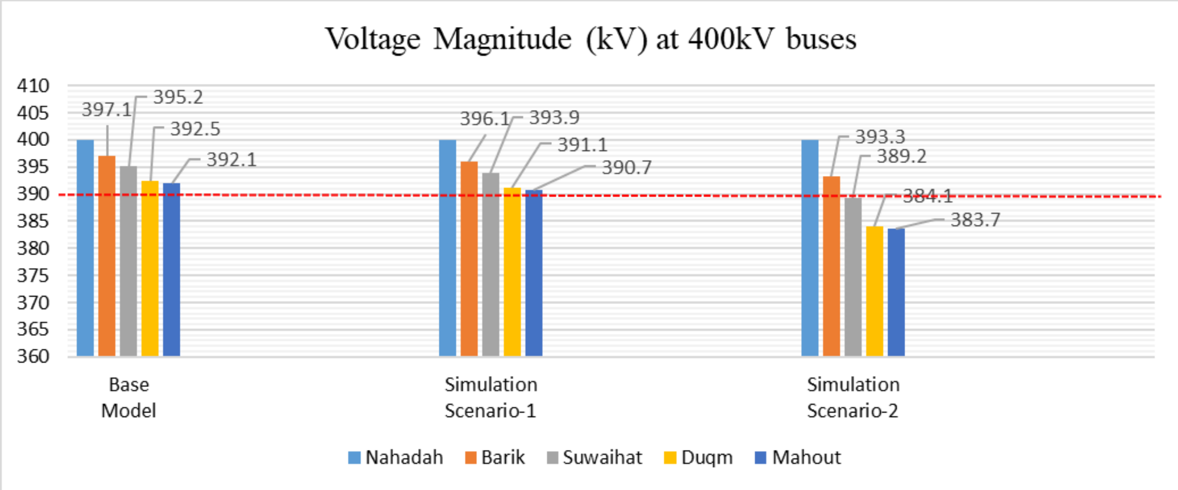

Figure. 3. Voltage magnitude at 400kV buses

5. DESIGN OF STATCOM FOR THE 400KV TRANSMISSION SYSTEM

During the design procedure of a STATCOM, different voltage source converter (VSC) components, including a ripple filter, an interface AC inductor, and the value of the DC capacitor must be estimated and selected. The voltage at the point of common coupling (PCC) is ripple-filtered to remove the switching ripples. To reduce the ripple in the currents and voltages, a ripple filter and interface inductors are designed [4][5]. The energy storage capacity required under transient conditions determines how a DC bus capacitor is designed. The required reactive power correction and level of load unbalance determine the STATCOM's rating. As a result, the load power rating of the STATCOM influences its current rating, and its voltage rating is influenced by the DC bus voltage [6][7][8][9]. As shown in Figure 4, a three-phase three-wire STATCOM consisting of a three-leg VSC, six IGBTs, three AC inductors, and a DC capacitor is used. The rating of the VSC components is determined by the required compensation that must be provided by STATCOM. The VSC is designed to compensate for a 125MVA reactive power in a three-phase, 33 kV, 50 Hz system (with a safety factor of 0.1). Table 4 illustrates the designed parameter values for the implemented STATCOM.

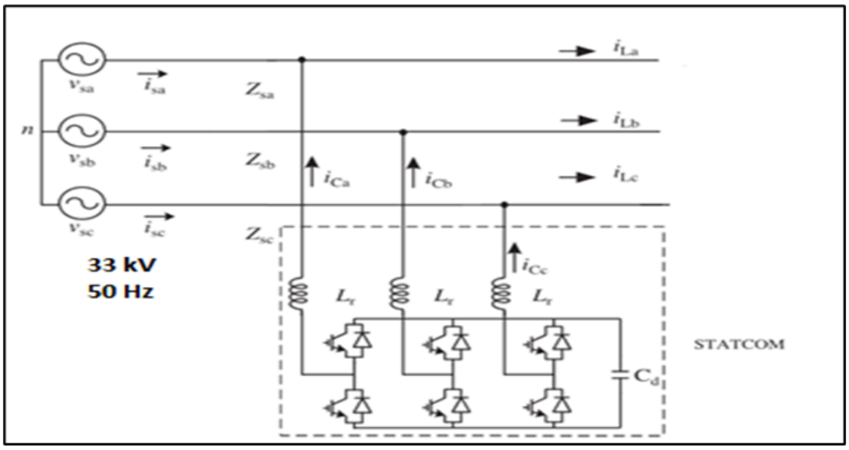

Figure. 4. Three-Phase Three-Wire STATCOM configuration [6].

Table 4. STATCOM Designed Parameters

DC Bus Voltage	54kV
DC Bus Capacitor	83 mF
AC Inductor	10 mH
Ripple Filter	R = 10 Ω, C = 5.5 μF
Solid-State Switches Ratings	69 kV, 6 KA

6. OPTIMIZATION FOR THE PLACEMENT OF STATCOM

The simulation of the studied 400kV transmission line connecting the north and south of Oman power systems is considered to be a base model with power exchange to PDO power system network through Nahadah, Barik, and Suwaihat grid stations which are supplying a total demand of 55.2 MW and 20.36 MVAR. In addition, the total demand in the Duqm grid station is 159.2 MW and 52.4 MVAR. Moreover, the total demand in Mahout grid station is 21.3 MW and 7 MVAR. The load flow simulation indicated that the voltage profile in the 400kV buses of Suwaihat, Duqm, and Mahout exceeds the allowable voltage limit (390kV-410kV). Figure 5 shows the voltage magnitude at 400kV buses considering the base model and different locations of the 125MVA designed STATCOM.

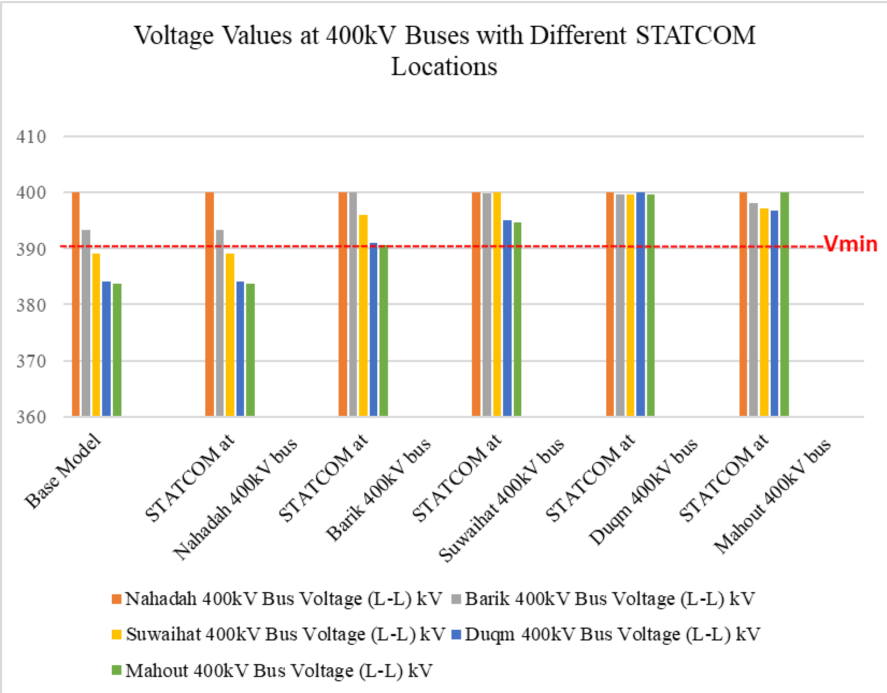

Figure. 5. Voltage values at 400kV buses with different STATCOM locations

The voltage values of the 400kV buses, when the STATCOM is connected to the Nahadah 400kV bus, remain the same without any enhancement due to the consideration of the Nahadah 400kV bus as a slack bus which eliminates the effect of STATCOM reactive power injection to the system. In addition, In the case of connecting the 125MVA STATCOM to the Barik 400kV bus, the overall system voltage profile is enhanced and the values of the voltage in the 400kV buses can be considered to be within the allowable operation limits. However, the value of the voltage magnitude at Mahout 400kV bus is 390.6 kV which is close to the minimum voltage limit (390kV). A better voltage profile enhancement can be indicated when the STATCOM is connected to Suwaihat 400 kV bus. The maximum voltage deviation, in this case, is found in Mahout 400kV bus with a voltage drop of 5.3 kV. The performance of the designed 125 MVA STATCOM showed an efficient effect on the studied 400 kV transmission system when it's connected to Duqm 400kV bus. All the 400kV buses are maintained with almost 400kV ignoring the minor voltage deviation of 0.4 kV in Suwaihat, Barik, and Mahout 400kV buses. Moreover, the reactive power set point of the STATCOM is maintained at 50.5 MVAR which highlights that the STATCOM rating of 50.5 and above will guarantee the ability of the STATCOM to raise the voltage to 400kV. The STATCOM reactive compensation raises the voltage magnitude of the 400kV buses when it's connected to Mahout 400kV bus with a maximum voltage deviation found in Duqm 400kV bus. The STATCOM reactive power set point is 75 MVAR when it's connected to the Mahout 400kV bus which is higher compared to the reactive power set point in the case of STATCOM connected to Duqm 400 kV bus. Eventually, the overall results prove the optimal location of the designed 125 MVA is in Duqm 400kV bus. In addition, installing the STATCOM in Duqm 400kV bus might be a cost-effective decision due to the lowest reactive set point required compared to the reactive power set point in the other locations as shown in table 5.

Table 5. STATCOM reactive power wet point

STATCOM Location	Nahadah 400kV bus	Barik 400kV bus	Suwaihat 400kV bus	Duqm 400kV bus	Mahout 400kV bus
Q set point MVA	125	108	103	50.5	75

7. CONCLUSION

In conclusion, this research paper underscores the critical importance of addressing voltage profile and stability concerns in the 400kV transmission interconnection project between northern and southern Oman. Through a comprehensive analysis utilizing advanced simulation tools, the study identifies potential challenges arising from increased energy demand and interconnection complexities. The proposed solution of deploying a carefully designed STATCOM emerges as a promising strategy to enhance voltage profiles and ensure system stability.

By examining various scenarios and load conditions, the research demonstrates that the optimal placement of the STATCOM at the Duqm 400kV bus can effectively counteract voltage deviations and improve overall system performance. The findings provide valuable guidance for power system planners and policymakers as Oman continues to advance its ambitious Vision 2040 development strategy. The successful implementation of the recommended STATCOM solution not only strengthens the interconnection's capacity and reliability but also aligns seamlessly with Oman's efforts to diversify its energy sources, foster economic growth, and embrace sustainable practices.

It is seen from the simulation results that STATCOM installation will start benefitting as the active and reactive power demands rise to 235.7 MW and 80.48 MVAr. A STATCOM at Duqm with a reactive power set point of 50.5 MVAR is the optimal solution to maintain the voltage profile at 400kV buses with a minimum voltage deviation percentage of 0.1%.

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