VOLTAGE STABILITY AND CONTROL OF NEW HAVEN 132/33KV POWER FEEDER USING DISTRIBUTED STATCOM

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ABSTRACT

Voltage stability issues are a major concern in Nigeria due to many system failures and surges in electrical installations around Enugu. Owing to the fact that D-STATCOM temporarily increases the nominal current (inductive or capacitive) of power system network, its application for voltage stability and control in power system network will proffer solution to the voltage network challenges to the network under study. The main aim of this work is to improve the voltage stability of the New-Haven 132/33kV network using distributed STATCOM. To achieve this, the case study was characterized to determine the voltage stability level of the network. The characterization was done using continuation power flow and voltage stability indices. Simulink model of the test network was then developed in PSAT platform. D-STATCOM is then configured and introduced at the weakest buses to improve the stability of the case study. The transformer and feeder data used for this work was from the New Haven 33kV load flow summary for the month of June, 2022. By connecting D-STATCOM at New NNPC bus as a point of common couple (PCC), the voltage magnitude of all the buses moved from 0.474pu to the IEEE approved range of 0.95-1.05pu.

Keywords: Voltage Stability and Control, New Haven 33kV, load-flow, STATCOM

1. INTRODUCTION

Demand for energy consumption in Nigeria has increased drastically. Nigeria's primary energy demand is electricity. In Nigeria as a country, the demand for electricity has increased due to the improved economic activity of the population. In order to efficiently meet the growing demand for energy, a complex construction of the electrical network is required (Samuel et al, 2017). Nigeria's complex electrical network consists of a power generation network, a transmission network or grid, and a distribution network. The complexity of interconnected power grids presents some complex technical challenges for grid operators. This problem can increase the administrative capacity of independent system operators responsible for monitoring the grid and ensuring the free flow of electricity, while burdening others with knowledge and experience in grid design (Samuel et al., 2017). Operators must rely on increasing powerful tools to solve the problem of predicting the performance of complex systems, one of which is ensuring voltage stability and control.

The generation station generates Electric power and transmission networks transmit the generated energy to the final stage of power transfer (distribution networks) where power is directly delivered to consumers by power utilities (Ethmane et al., 2019) . Voltage stability problems are a major concern in South East Nigeria due to the high frequency of system failures and surges in installed electrical equipment. In many power systems, voltage stability assessment and voltage stability and regulatory forecasting have become key forms of analysis performed as part of system planning, operational planning, and real-time operation (Abdulkareem et al., 2016). In other words, voltage stability and control is the ability of the system to maintain voltage with respect to load acceptance, while the ability to provide reactive power reduction under constant operating conditions is an important aspect of voltage stability and control. Voltage stability refers to the ability to control the voltage level within a narrow range around the normal operating voltage.

A static VAR compensator is used to improve voltage stability because of the opening line in the presence of the induction motor or due to start induction motor or because of recoveries of short circuit motor terminals or due to heavy load capacity. It consists of either load flow or steady state stability methods. Static analysis is useful for indicating the possibility of voltage collapse (Shehata et al., 2021). Voltage Stability Indices (VSI) is approximations used in this study to determine the voltage stability of a power system. A VSI is an updated parameter for tracking changes in the system. It is one of the easiest and most accurate methods to determine the stability of power systems today. VSI can be divided into two approaches: Jacobian matrix-based VSI and system variable-based VSI.
There are two major families based on the three -phase voltage composition in the electrical distribution. On the other hand, the system connects the system "D -face (faces (flexible alternate current transmission) and interface to the second and second centralized energy producers. Power electronics based systems can be networked with a series compensator such as a dynamic voltage restorer (DVR) or a shunt compensator such as a distributed static compensator (D-STATCOM) and can use modes of active or passive compensation (Enemuoh et al., 2013). Because of the shunt connection, the inverter voltage is referred to as D-STATCOM (D for divider, STATCOM for static compensator) due to the misuse of the language. The language of negative use is due to the fact that the guaranteed function significantly exceeds reactive power exchange, maintaining the voltage level of the network and reactive power exchange and sometimes damping some oscillations (Nor and Sulaiman, 2019). The research presented in this paper is based on voltage regulation for reactive power shunt compensation using a FACTS element-based D-STATCOM voltage converter. A complete simulation of DSTATCOM is carried out in MATLAB/SIMULINK, introduced into the distribution network and presented to validate the operation of this device in both modes of capacitive and inductive compensation (Sathvik et al., 2019).
Poor management of reactive power in New Haven 33kV feeder distribution network has caused a lot of harm than good in the network and/or the society at large. Poor quality of power emanating from this network and environs has resulted in high loss of power with mostly low output voltages. This has resulted in the loss of high voltage components/equipment ranging from transformer, insulators in distribution lines to total loss

of high voltage power substation with power outage especially when the reactive power continues to rise with current. Due to the high number of system faults, voltage stability problems become a major challenge which can cause electrically installed equipment stress up over time.

The purpose of this study cannot be over emphasized. It is cleared that both controllable and uncontrollable factors affect lower system. For instance, then system voltage increases when the reactive load decreases and the system voltage also decreases when the power bus capacity decreases. These unit helps to balance when the power to maintain system stability. Often at increase load levels the transmission voltage will reach its real and reactive power limits due to line power current exceeding the limit. These events can change the equations that model the power output. With the important attributes of calibration device or process which is response time, New Haven 33kV calls for increased ability of independent system operations to monitor the grid and ensure the free flow of electricity while others may limit their knowledge and experience in grid design. Power systems suffer from the following events (voltage and current) and power system parameters (real and reactive power). Power system conditions and parameters are influenced by both controllable and uncontrollable factors (Rao et al., 2012). Voltage stability and regulation issues have been addressed in many studies around the world which is discussing how to address this pressing issue. The point where the voltage instability in that area overwhelms the electric driven wheel is often referred to as the critical point. The study of the critical point is important because determining the critical point indirectly defines the boundary between stable and unstable regions of operation (Lele et al., 2022). However, nonlinearity leads to complex and unpredictable behavior in many systems; a distinctive feature observed in many nonlinear systems is the sudden change in steady-state behavior that can occur if a parameter changes uniformly. Drastically changing parameter values usually correspond to singularities in the governing equations. As a developing country, the demand for electricity in Nigeria has increased due to the improved economic activity of the population. The aim of this paper is to ensure voltage stability to control the New Heaven 33kV power system network using distributed STATCOM with the following specific objectives:

i. To characterize the New-Haven, 33KV feeder distribution network using continuation load flow study and hence determine the stability level of the network.
ii. To configure the D-STATCOM in PSAT and connect it to New-Haven, 33KV feeder bus of the test network for optimum compensation.
iii. Again, to perform a continuation load flow study on the compensated network to evaluate the Performance of the technique used.

2. RESEARCH METHODOLOGY

To enhance the method employed in this study the figure 1 present the flow chart, while the device/equipment needed include: A HP Laptop computer used for simulation, MATLAB and Simulink software, power system analysis tool box (PSAT) used for modeling in Simulink the test network understudy and bus and line data of the network.

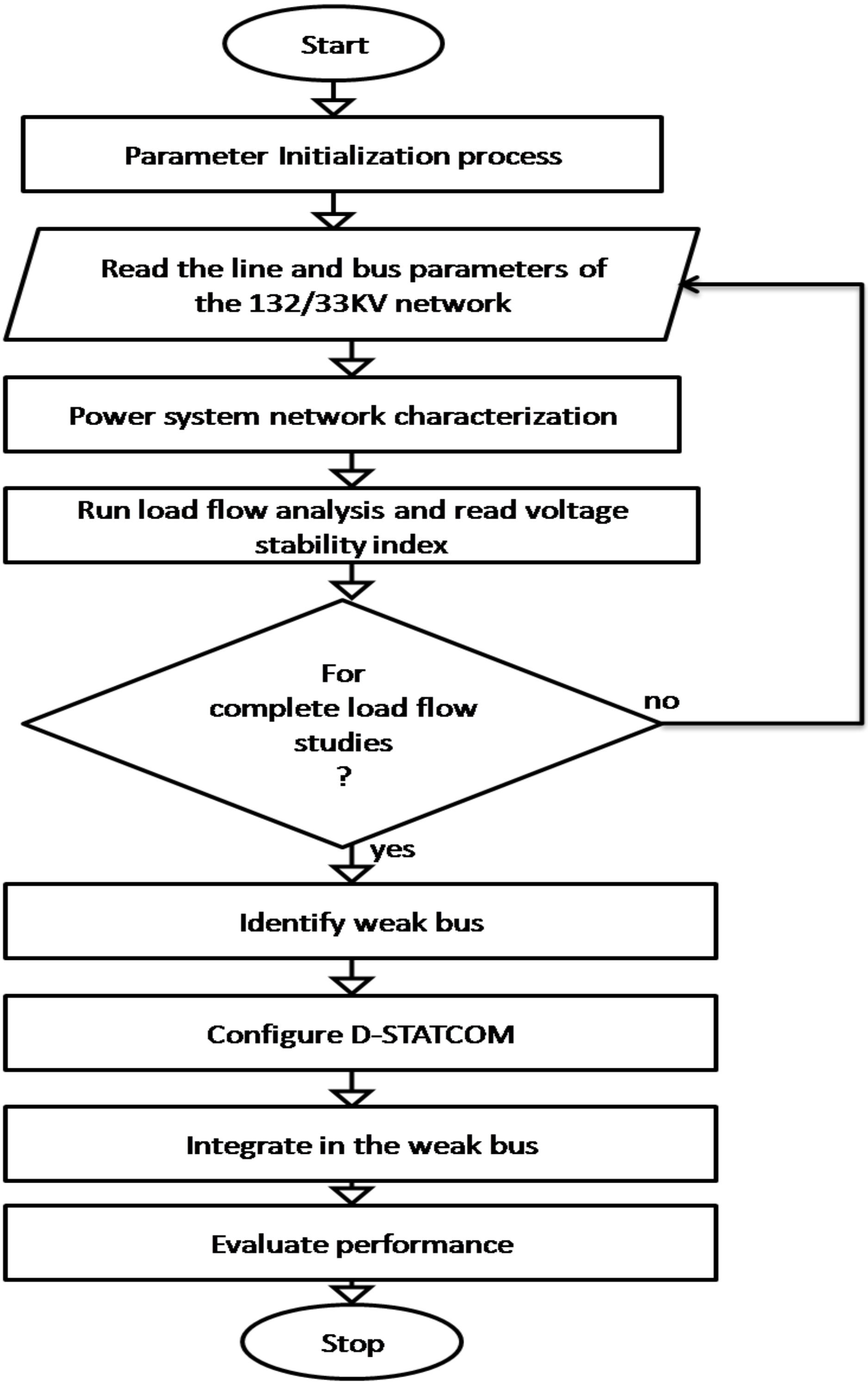

Figure 1: Study flow chart and load flow analysis

First, the network under sturdy was characterized to determine the level of stability using continuation load flow sturdy. A Simulink model of the test network was developed in PSAT and D-STATCOM configured model were introduced at the weakest buses and simulated to find out the level of voltage stability the results were compared with those obtained earlier driving characterization to determine the percentage voltage stability improvement in the network.The D-STATCOM is a static synchronous generator that generates a synchronous three-phase alternating voltage with the mains voltage from a direct voltage source. The amplitude of the voltage of DSTATCOM may be controlled to adjust the measure of reactive power to share with the network (Rafi et al., 2022). D-STATCOM for three-phase shunt-connected voltage source converter (VSC) is designed for use in power distribution networks for bus voltage compensation to provide better power factor and reactive power control (Mokhtari et al., 2014). These devices can inject or support active and reactive power at a common connection point (PCC). The limitations associated with energy storage make it impossible for the D-STATCOM to input active power for long periods of time.The main advantages of the DSTATCOM are its ability to generate rated current at almost any line voltage, good dynamic response, and relatively small capacitor usage on the DC bus (Satvik et al., 2019).

According to Suliman, (2020) STATCOM on the load side for compensating the load voltage. Start by testing the pattern and changing the load, continuing to measure the voltage on the load bus. Compensation is performed at t=0.65 seconds for a balanced load. The results show that the load voltage drop increased proportionally with increasing load, the maximum drop (0.8 pu) between 0.33 s and 0.65 s, respectively. The result of off-load operation to compensate the load voltage for an unbalanced condition. STATCOM smoothes and recovers load voltage drops after 0.5 seconds. The load current before and after compensation, this compensation process is done by the DSTATCOM injection voltage, where the phase voltage is the FFT analysis of BB3 bus voltage, the total harmonic distortion THD after DSTATCOM injection was 0.22%. The result of the characterization was presented as;

Table 1: Line data from New Haven Transmission for the month of June 2022

NETWORK	PEAK LOAD (MW)	VOLTAGE (KV)	MAX VOL (KV)	LENGTH (KM)	KW	KVA	KVAR
N/HAVEN TR1	17.9	33	33.5		1790	2237.5	1342.5
NEW NNPC	5.4	33	33.5	24.32	540	675	405
IND LAYOUT	15.2	33	33.5	3.44	1520	1900	1140
NEW HAVEN	3.95	33	33.5	1	395	493.75	296.25

Table 2: Bus data from New Haven Transmission for the month of June 2022

Bus	V(pu)	Phase (rad)	P gen(pu)	Q gen(pu)	P load(pu)	Q load(pu)
N/HAVEN TR1	1.2504	-0.6484	-1.98E-06	-2.41E-05	0	0
NEW NNPC	0.7295	-0.6484	-2.16E-07	4.52E-07	0.28668	0.26168
IND LAYOUT	0.7295	-0.6484	4.33E-06	3.03E-05	0.51193	0.04893
NEW HAVEN	0.7295	-0.6485	3.76E-06	5.20E-07	0.56312	0.26168

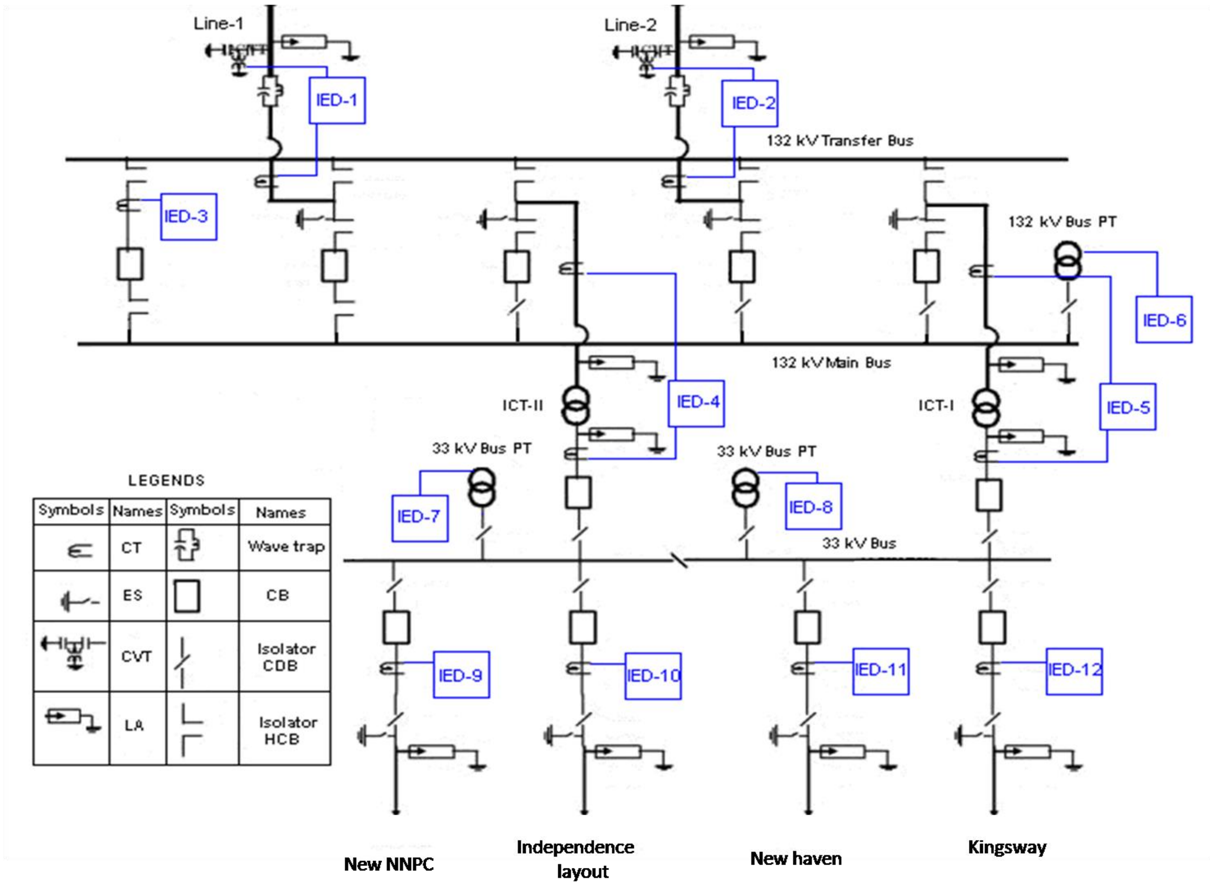

Figure 2: Line diagram of the New-Haven 33kV feeder distribution Network

2.1 The Continuation of Power Flow

The Jacobian matrix of the current-power equation becomes singular at the limit of voltage stability. Continuing the flow of power solves this problem. Continuous power flow finds a continuous load flow solution according to the load scenario. It consists of evaluation and correction stages. A critical point is a point whose tangent vector is zero. An image of the predictor-corrector scheme is shown in Figure 3;

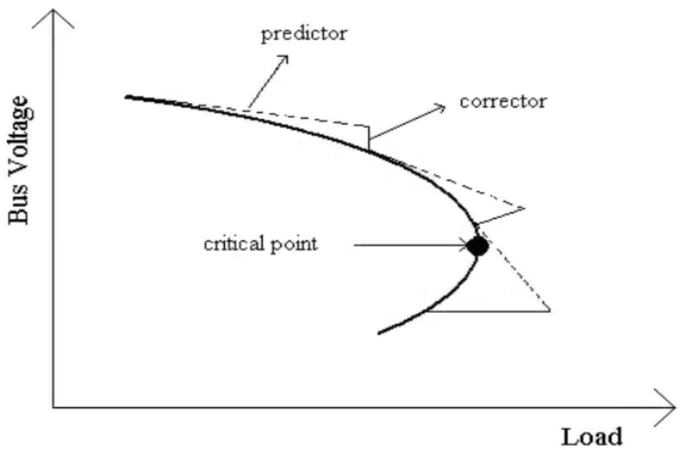

Figure 3: Illustration of prediction-correction steps (Mehmet, 2007)

In continuation load flow, first power flow equations are reformulated by inserting a load parameter into these equations (Adesakin et al., 2020).

Injected powers can be written for the i^{th} bus of an n-bus system as follows (Bergen, 2000) in (Farrokhseresht, 2015) :

$$\mathbf{P_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik})}$$
$$\mathbf{Q_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin\theta_{ik} + B_{ik}\cos\theta_{ik})} \qquad (1)$$
$$\mathbf{P_i = P_{Gi} - P_{Di},\ Q_i = Q_{Gi} - Q_{Di},} \qquad (2)$$

where the subscripts G and D denote generation and load demand respectivelyon the related bus.In order to simulate a load change, a load parameter λ is inserted into demandPowers P_{Di} and Q_{Di}

$$\mathbf{P_{Di} = P_{Dio} + \lambda(P_{\Delta base})}$$
$$\mathbf{Q_{Di} = Q_{Dio} + \lambda(Q_{\Delta base})} \qquad (3)$$

P_{Di0} andQ_{Dio} are original load demands on i_{th}bus whereas $P_{\Delta base}$ and $Q_{\Delta base}$ are given quantities of powers chosen to scale λ appropriately. After substituting new demand powers from equations (1) to equations (3), new set of equations can be represented as:

$$\mathbf{F(\Theta, V, \lambda) = 0} \qquad (4)$$

Where Θ denotes the vector of bus voltage angles and V denotes the vector of bus voltage magnitudes. The base solution for λ = 0 is found via a power flow.

Then, the continuation and parameterization processes are applied (Wesley et al., 2022)

Prediction Step

In this step, a linear approximation is used by taking an appropriately sized step in a direction tangent to the solution path. Therefore, the derivative of both sides of equation (4) is taken.

$$\mathbf{F_\Theta d\,\Theta + F_v dV + F_\lambda d\,\lambda = 0}$$
$$\mathbf{[F_\theta F_v F_\lambda]\begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix} = 0} \qquad (5)$$

In order to solve Equation (5) one more equation is needed since an unknown variable λ is added to load flow equations. This can be satisfied by setting one of the tangent vector components to +1 or -1 which is also called continuation parameter. Setting one of the tangent vector components +1 or -1 imposes a non-zero value on the tangent vector and makes Jacobian nonsingular at the critical point. As a result, Equation (5) becomes:

$$\mathbf{\begin{bmatrix} F_\theta & F_v & F_\lambda \\ & e_k & \end{bmatrix}\begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix}} \qquad (6)$$

Where e_k is the appropriate row vector with all elements equal to zero except thek^{th} element equals 1. At first step λ is chosen as the continuation parameter. As the process continues, the state variable with the greatest rate of change is selected as continuation parameter due to nature of parameterization. By solving Equation (6), the tangent vector can be found. Then, the prediction can be made as follows:

$$\mathbf{\begin{bmatrix} \theta \\ V \\ \lambda \end{bmatrix} P + 1 \begin{bmatrix} \theta \\ V \\ \lambda \end{bmatrix} + \sigma \begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix}} \qquad (7)$$

Where the subscript “p+1” denotes the next predicted solution. The step size σ is chosen so that the predicted solution is within the radius of convergence of the corrector. If it is not satisfied, a smaller step size is chosen.

2.2 Correction Step

In correction step, the predicted solution is corrected by using local parameterization. The original set of equation is increased by one equation that specifies the value of state variable chosen and it results in:

$$\begin{bmatrix} \mathbf{F}\,(\boldsymbol{\theta}, \mathbf{V}, \quad \boldsymbol{\lambda}) \\ \mathbf{X_K} - \eta \end{bmatrix} = [\ \mathbf{0}\ ] \qquad (\mathbf{8})$$

Where x_k is the state variable chosen as continuation parameter and η is the predicted value of this state variable. Equation (8) can be solved by using a slightly modified Newton-Raphson power flow method.

Parameterization

It is important to choose an expansion option when continuing the flow of power. The next parameter is the state variable with the highest rate of change. Initially, λ is chosen as a continuous parameter because there is little change in tire stress and angle due to light loading in the first stage. As the load increases over several stages, the solution approaches a critical point and the rate of change of the tire stress and angle increases. Therefore, various control parameters are checked after each debugging step. The variable with the largest change is chosen as the next parameter. In the indirect vector of equation (8), +1 is used when the parameter increases and -1 is used when the parameter decreases.

Continuation Load flow is performed on the test network in order to determine the variables of the system under maximum stress condition of the network. Some of these variables are: voltage magnitude, injected real power and Injected reactive power. Continuation Load flow sturdy gives an insight into the stability of the network. For the system to be stable, voltage profile of all the buses must lie between the IEEE approved range of 0.95 to 1.05pu (Nor & Sulaiman, 2019). The bus with the lowest voltage profile assumes the weakest bus, in performing continuation load flow on case study network, MATLAB environment was opened and PSAT was launched. The Simulink model of the test network first loaded to the system through the PSAT interface. PSAT extracts the bus and line data from the inputted Simulink model. Continuation power flow was then run by pressing the 'runs continuation power flow' button. The generated report is obtained from the static report icon of the PSAT interface. This feature allows STATCOM to supply constant reactive power at the limits and has placed it in an advantageous position when compared to other power electronics tools. Figure 4 shows the rudimentary structure of a STATCOM; while figure 5 presented the integration of the STATCOM on the power system network.

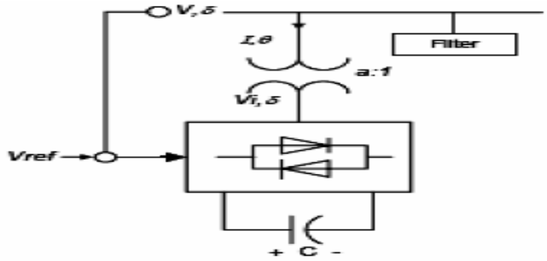

Figure 4 Basic Structure of STATCOM

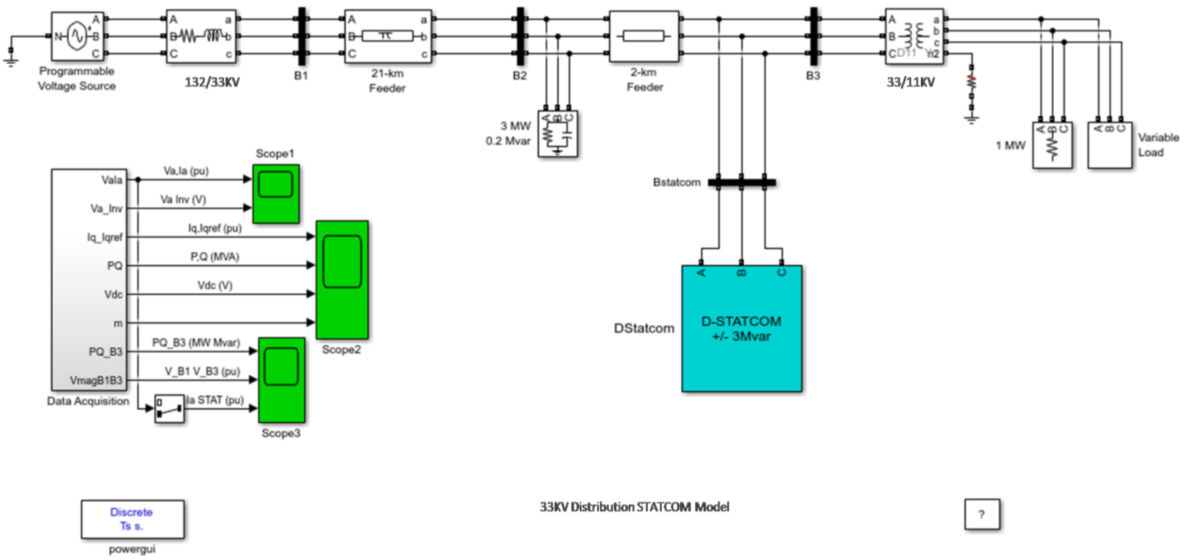

Figure 5: Simulink model of the power system network

3.1 RESULT AND DISCUSSION

This section presented the results of the loaf flow analysis on the power system network with the D-STATCOM and then compared with the characterized system without STATCOM to validate the result.

Table 1: Result of Continuation Load flow for June 2022

Bus	V(pu)	Phase (rad)	P gen(pu)	Q gen(pu)	P load(pu)	Q load(pu)
N/HAVEN TR1	1.2504	-0.6484	-1.98E-06	-2.41E-05	0	0
NEW HAVEN	0.7295	-0.6485	3.76E-06	5.20E-07	0.56312	0.26168
IND LAYOUT	0.7295	-0.6484	4.33E-06	3.03E-05	0.51193	0.04893
NEW NNPC	0.7295	-0.6484	-2.16E-07	4.52E-07	0.28668	0.26168

Table 2: Result of Continuation Load flow when real Load is increased by 15MW

Bus	V(pu)	Phase (rad)	P gen(pu)	Q gen(pu)	P load(pu)	Q load(pu)
N/HAVEN TR1	0.5617	-0.5473	-3.96E-08	-4.82E-06	0	0
NEW HAVEN	0.9628	-0.5474	7.52E-08	1.04E-07	0.39419	0.26168
IND LAYOUT	0.5617	-0.5474	8.66E-08	6.05E-06	0.35835	0.04893
NEW NNPC	0.9628	-0.5474	-4.32E-09	9.03E-08	0.20068	0.26168

Table 3: Result of Load flow load increased to 25MW before Compensation

Bus	V(pu)	phase(rad)	P gen(pu)	Q gen(pu)	P load(pu)	Q load(pu)
N/HAVEN TR1	0.4741617	-0.4214418	-2.20E-8	-2.80E-6	0	0

NEW HAVEN	0.4741502	-0.421496	4.18E-8	6.05E-7	0.365665	0.163552
IND LAYOUT	0.4741596	-0.4214911	4.81E-5	3.52E-8	0.3324228	0.0305829
NEW NNPC	0.4741502	-0.4214694	-2.40E-6	5.25E-9	0.1861568	0.163552

Table 4: Result of Continuation Load flow after Compensation

Bus	V(pu)	phase(rad)	P gen (pu)	Q gen(pu)	P load(pu)	Q load(pu)
N/HAVEN TR1	0.975212	0.008621	-2.67E-5	1.00E-4.	0	0
NEW HAVEN	0.975212	0.00862	1.30E-6	-7.47E-5	0.165	0.0738
IND LAYOUT	0.975212	0.00862	5.11E-6	-5.65E-5	0.15	0.0138
NEW NNPC	0.975208	0.00862	4.11E-6	-3.24E-5	0.084	0.0738

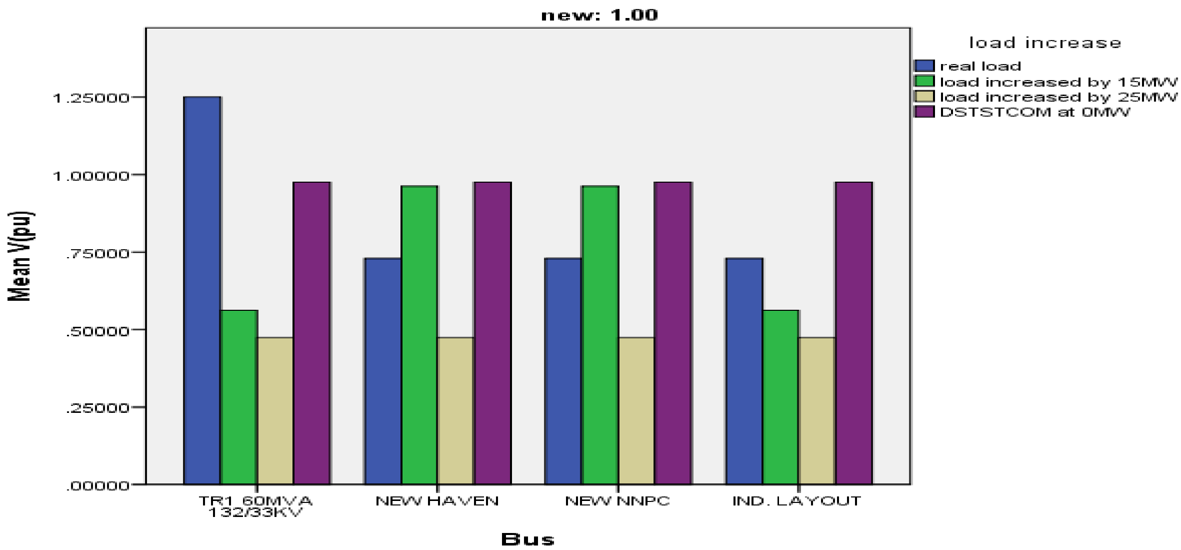

Figure 6: Bar chart showing voltage magnitude of test network buses before and after compensation

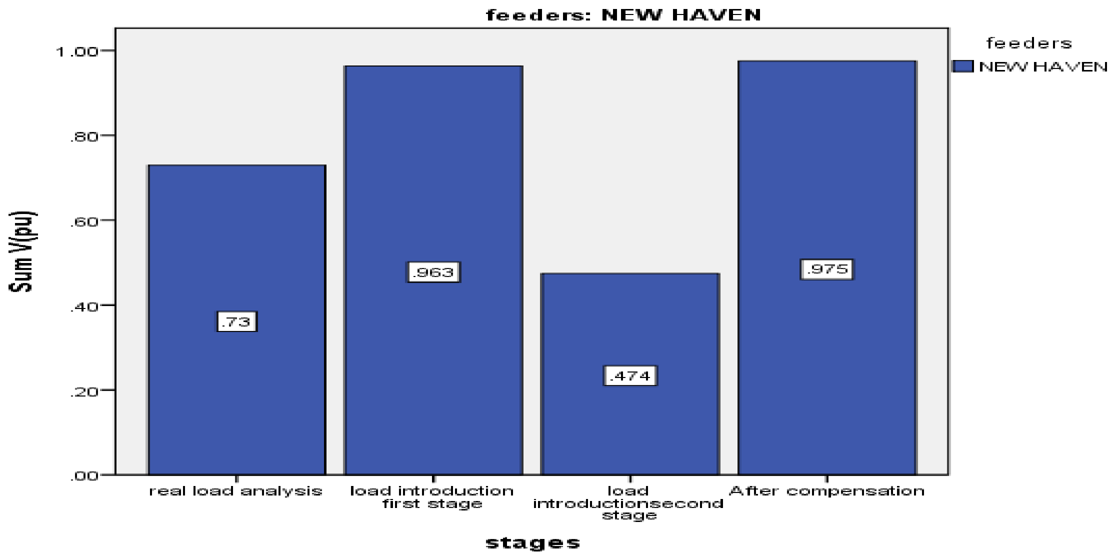

Figure 7: Bar chart showing the impact of DSTATCOM on voltage magnitude of test network buses at the voltage drag below IEE standard and after compensation

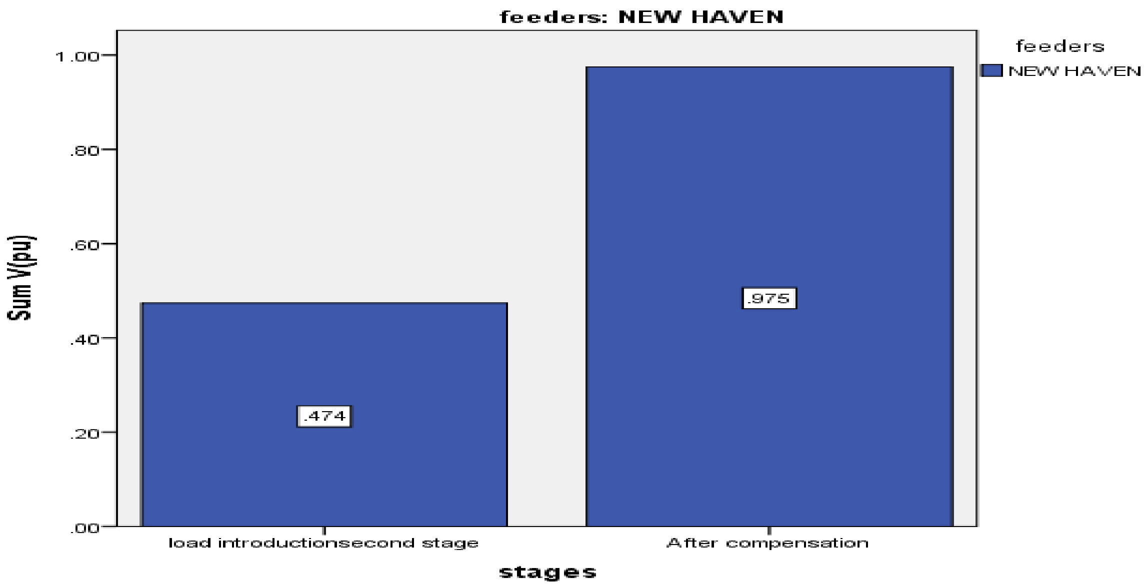

Figure 8: Bar chart showing voltage drag to near collapse with continuity load flow analysis and the impact of DSTATCOM on busting the voltage magnitude after compensation

Table 5: Summary of New haven 33kV feeder Result of Continuation Load flow before and after Compensation

Bus	V(pu)	phase(rad)	P gen (pu)	Q gen(pu)	P load(pu)	Q load(pu)
NEW HAVEN	0.7295	-0.6485	3.76E-06	5.20E-07	0.56312	0.26168
NEW HAVEN	0.9628	-0.5474	7.52E-08	1.04E-07	0.39419	0.26168
NEW HAVEN	0.4742	-0.421496	4.18E-8	6.05E-7	0.365665	0.163552
NEW HAVEN	0.9752	0.00862	1.30E-6	-7.47E-5	0.165	0.0738

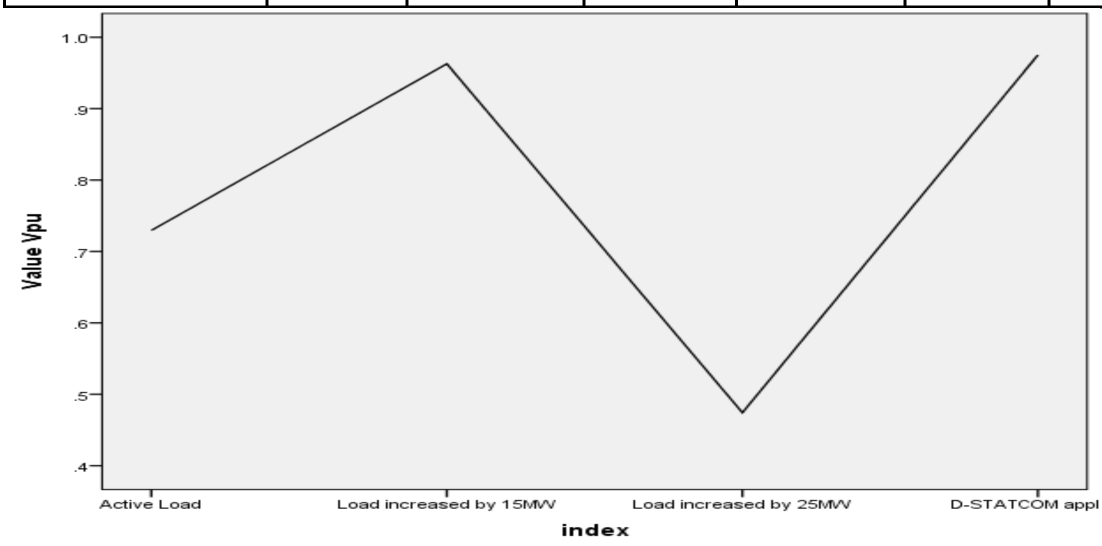

Figure 9: Line graph showing the impact of DSTATCOM on voltage magnitude of test network buses at the voltage drag below IEE standard and after compensation

The graph in figure 9 shows those as the active power is increasing the voltage drops, meaning that to deliver such load are near impossible, because by IEE standard the voltage magnitude cannot wheel such increase in real load. Hence, the application of D-STATCOM will compensate the voltage and boost it to IEE standard. The regulator gains of DSTATCOM are obtained by applying the VSI with objective function to minimize the error signal between the actual measured voltage and reference voltage (1pu), by applying automatic switch control the VSI is employed for 1 event created between the extreme swell event and extreme sag event.

3.1 DISCUSSIONS OF RESULTS OBTAINED

This shows that the network requires compensation to overcome this voltage instability. It is also clear that New–Haven 33kV feeder bus with a voltage magnitude of 0.474pu is weak and requires compensation. This implies that as D-STATCOM is connected to a bus with weak voltage magnitude it will improve and the voltage will be stable.

The result shows that D-STATCOM was effective in enhancing the voltage stability of the test network from 0.474pu to 0.975pu.

Voltage Profile Stability Index (VPSI) can be computed as follows:

$$\textbf{(VPSM)} = \frac{\mathbf{0.975-0.474}}{\mathbf{0.474}} \ \mathbf{x\ 100\%} \qquad = \mathbf{105.6\%}$$

This shows that D-STATCOM enhanced the voltage stability of the test network by 105.6%

3. CONCLUSION AND RECOMMENDATIONS

The voltage stability improvement of the New Haven 33kV feeder distribution network is 105% was achieved, when the D-STATCOM was placed at the weak bus (New Haven). It can also be concluded that continuation power flow is a powerful tool in characterizing the voltage stability of a distribution network. In recommendation, continuation load flow studies together with D-STATCOM form a powerful tool for combating voltage instability to restore power quality in distribution network

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