IMPROVING STATIC VOLTAGE STABILITY IN THE SUDAN NATIONAL GRID

Sideig Abdelrhman Dowi[1], Osman Abdeen Osman[2], Mohamed Alnour Mustaffa[3] and Osama Mohammed Elmardi[4]

[1,2,3]Department of Electrical and Electronic Engineering, Nile Valley University, Atbara-Sudan
[4]Department of Mechanical Engineering, Nile Valley University, Atbara-Sudan
Corresponding Author: osamamm64@gmail.com

Abstract
Enhancing static voltage stability in Sudan's national grid is vital for improving the reliability and efficiency of its electricity supply system, especially as the country develops its power infrastructure to meet rising demand. This involves employing advanced control strategies, integrating reactive power support systems like Static Var Compensators (SVCs) and Flexible AC Transmission Systems (FACTS), and optimizing transmission line configurations to manage variability in demand effectively. Moreover, real-time monitoring and data analytics are crucial for preemptively identifying instability issues. This paper evaluates the Sudan National Grid's performance concerning growing demand and reactive power resources, using the V-Q sensitivity method to identify the weakest buses and NEPLAN software for analysis. By implementing these enhancements, Sudan can achieve a more resilient and stable grid, supporting economic growth and improving citizens' quality of life.
Keywords: load flow analysis, SVC, Modal analysis, V-Q sensitivity analysis, Active power index (VPI-bus), Reactive power index (VQI-bus).

1. Introduction

The conception of voltage stability is related to transient stability of a power system [1]. Many phenomena cause the actual voltage different from the nominal value. Unacceptable voltage level means that voltage instability. If the voltage departs too much from the nominal value, the voltage collapse will occur [2]. As a result of voltage instability, a power system undergoes voltage loss if the post-disturbance equilibrium voltages close to loads are below reasonable limits. The voltage stability is related to the control of the reactive power. The Flexible AC Transmission System (FACTS) becomes the control of the reactive power flow more dynamic, since the acquired flexibility on the transmission system [3]. The optimum location of FACTS devices is a very important issue in power systems, since the weakest busbar and/or transmission lines need to be identified [4],[5], and [6].

Static voltage stability enhancement of the Sudan national grid is a critical area of focus for improving the overall reliability and efficiency of the country's electricity supply system. As Sudan continues to develop its power infrastructure to meet growing demand, addressing static voltage stability becomes paramount. This involves implementing advanced control strategies and technologies to maintain voltage levels within acceptable limits, especially during peak load conditions and disturbances. Enhancements can be achieved through the integration of reactive power support systems, such as Static Var Compensators (SVCs) and Flexible AC Transmission Systems (FACTS), which help to stabilize voltage profiles by swiftly responding to fluctuations in load and generation. Additionally, optimization of transmission line configurations and reinforcement of the network can improve the ability of the grid to handle variability in demand while minimizing losses. Furthermore, enhancing voltage stability also necessitates rigorous monitoring and real-time data analytics to identify potential instability issues before they escalate. By investing in these enhancements, Sudan can ensure a more resilient and stable national grid, ultimately supporting its economic growth and improving the quality of life for its citizens.

2. Literature Review

Voltage stability and the risk of voltage collapse have emerged as critical issues in contemporary power systems. In today’s deregulated market environment, power systems are often pushed to their maximum operational limits to enhance the utilization of existing infrastructure. This high-stress operating condition makes the system particularly vulnerable to any network outages or disturbances. Consequently, it is essential to analyze how the system responds under prolonged overload conditions and in the face of unexpected disruptions.

Formal definitions of voltage stability-related concepts can be found in references [7] and [8]. Voltage stability refers to a power system's capability to maintain its voltage levels despite increases in load admittance and power demand, thereby ensuring effective control over both power and voltage. The phenomenon through which voltage instability escalates into widespread voltage loss within a significant portion of the power system is termed voltage collapse. Meanwhile, voltage security denotes the ability of a power system to operate not only in a stable state but also to remain stable after experiencing reasonable contingencies or adverse changes in the system.

A power system can transform into an unstable state when disturbances such as increased load, the outage of a transmission line, or other alterations to the system prompt a rapid voltage drop or a gradual decline. In such scenarios, the failure of automatic control systems to restore voltage levels exacerbates the issue. This voltage decline can unfold over a period ranging from a few seconds to several minutes, underscoring the urgency of monitoring and managing voltage stability to prevent severe repercussions in the power system.

During the year 2003, a number of blackouts occurred over a span of less than two months affecting millions of people around the world. Some of them are:

Cascading failure of transmission and generation outages, which caused worst ever blackouts in the history of Northeast United states and Canada, on 14 August. Blackout left more than 50 million people in the dark [9], and [10].

Line faults followed by line tripping and malfunctioning of protection relays caused a blackout affecting 5 million people in Sweden and Denmark on 23 September. A similar blackout happened in Italy on 28 September, which has left 57 million people in the dark. This is one of the worst blackouts in Europe [9], and [10].

Another blackout, which is different from the United States and Europe, occurred in United Kingdom on 28 August due to transformer outage and a faulty relay operation [9], and [10].

From the above-mentioned blackouts along with the respective causes for blackouts, it is clear that the slower acting devices such as on load tap changers, generator over excitation limiters, characteristics of the system loads and also fast acting devices such as induction motors, excitation system of synchronous machines and compensation devices contribute to the evolution of voltage collapse due to sudden disturbances in the power system [11] – [13].

3. Voltage Stability Analysis

There are two general types of tools for voltage stability analysis; dynamic analysis tools and static analysis tools [14]. Dynamic analysis uses time-domain simulations to solve nonlinear systems of differential algebraic equations, while static analysis is based on solution of conventional or modified power flow equations [8]. Static analysis involves only the solution of algebraic equations, and is computationally considered more efficient than dynamic analysis. Therefore, static analysis is ideal for voltage stability studies of the bulk systems in which voltage stability limits for many pre-contingencies and post contingency cases must be determined. For these reasons static analysis methods of voltage stability are considered [14],[15], and [16].

3.1 Static VAR Compensator (SVC)

Static VAR Compensator is one of the most important shunt controllers in FACTS technology [17]. It is a shunt connected static VAR generator whose output is designed to draw capacitive or inductive current to maintain normal voltage at the bus which the SVC is installed. SVC is based on thyristor without the gate turn-off capability. It includes thyristor-controlled reactor (TCR) in parallel with fixed capacitor in it commonest form and is known as fixed capacitor thyristor controlled reactor type SVC for better control as it shown in Figure 1.

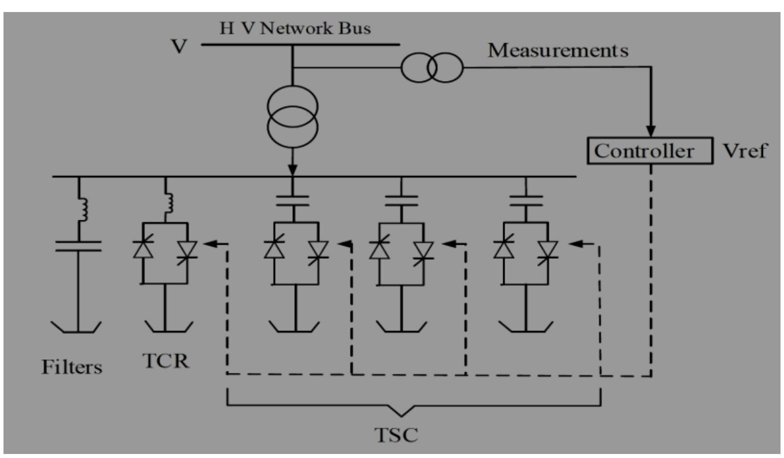


Figure 1: Configuration of Static VAR Compensator (SVC)

A simple and effective way to include the SVC in power flow techniques is to use this device as a variable susceptance. the shunt susceptance represents the total SVC susceptance necessary to maintain the voltage magnitude at the bus at specified value.

The inclusion of SVC at any load node makes that node becomes voltage-controlled node [6]. The variable susceptance B_{SVC} is operated as a state variable. The philosophy is that when the B_{SVC} is within the limits the specified voltage is attained and the bus operated as a PV bus. Therefore, if B_{SVC} is above or lower than the limits, it becomes fixed at the violated limit, and the node becomes a PQ bus again if there is no other voltage regulating equipment present. Then the current drawn by the SVC in node j is:

$$I = jB_{svc}V_j \tag{1}$$

The active and reactive power drawn by the SVC connected at node j given by

$$P_j = 0, \qquad Q_j = -|V_j|^2 B_{svc} \tag{2}$$

Also, the mismatches are given as

$$\begin{vmatrix} \Delta P_j \\ \Delta Q_j \end{vmatrix} = \begin{vmatrix} 0 & 0 \\ 0 & \dfrac{\partial Q_j}{\partial B_{svc}} \end{vmatrix} \begin{vmatrix} \Delta Q_j \\ \Delta B_{svc} \end{vmatrix} \tag{3}$$

At the end of iteration p, the variable shunt susceptance is corrected as

$$B_{svc}^{(p+1)} = B_{svc}^{(p)} + \Delta B_{svc}^{(p)} \tag{4}$$

Where, V_j = voltage at bus j

B_{svc} = is the Susceptance of SVC

Q_{SVC}= reactive power drawn by SVC.

I_{SVC}= the current drawn by the SVC.

Q_j= reactive power at bus j.

P_j= active power at bus j.

SVC compensation may also be computed in terms of thyristor firing angle.

The steady state susceptance of SVC can be obtained as

$$B_{svc} = B_c - B_{TCR} = \frac{1}{X_c X_l}\left[X_l - \frac{X_c}{\pi}\left(2(\pi - \alpha)\right) + \sin(2\alpha)\right] \tag{5}$$

$$Q_j = \frac{V_j^2}{X_c X_l}\left[X_l - \frac{X_c}{\pi}\left(2(\pi - \alpha)\right) + \sin(2\alpha)\right] \tag{6}$$

Assuming Qj is the jth bus reactive power injection due to SVC installation at jth bus, then, the linearized SVC equation is written as

$$\begin{bmatrix} P_j \\ Q_j \end{bmatrix}^{(p+1)} = \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{2V_j^2}{\pi X_l}\left[\cos(2\alpha) - 1\right] \end{bmatrix}^{(p+1)} \begin{bmatrix} \Delta\delta_j \\ \Delta\alpha \end{bmatrix}^{(p+1)} \tag{7}$$

At the end of iteration (P), the variable firing angle α is updated by the following equation

$$\alpha^{p+1} = \alpha^p + \Delta\alpha^p \tag{8}$$

$$V_j = V_{ref} + X_l I_{svc} \tag{9}$$

3.2 V–Q Sensitivity Analysis

The voltage sensitivity method is the most direct approach using the voltage sensitivity to system parameter. V–Q Sensitivity method gives the relationship between the voltage change and the reactive power changes at different buses by using reduced power flow Jacobian matrix [5], and [18].
Consider the linearized equation of power flow is

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{10}$$

If ΔP =0, then $\Delta Q = J_R \Delta V$, Where the reduced Jacobian matrix is

$$J_R = \left[J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV} \right]$$

(11)

Also, $\Delta V = J_R^{-1} \Delta Q$, the elements of the J_R^{-1} matrix are V_Q sensitivities. The self-sensitivities are represented by the diagonal of the matrix, in the other hand the non-diagonal elements are represents the mutual sensitivities. Positive sensitivity, system is stable. Negative sensitivity system is unstable [18].

3.3 Determination of Optimal SVC Rating

The rating or setting determination of SVC is also an important criterion for optimal SVC placement as the total investment cost depends on the rating of the equipment. The relation for choosing SVC rating is expressed as in [4], and [6].

4. Case Study

The simplified transmission network of Sudan National Grid consists of four 500kV substation and thirty-five 220kV substations. The maximum power can be generated from the SNG is about 2086.276 MW and 472.999 MVAR which it comes from eight power plants namely are Merwe dam, Garri, Roseires, Sennar, Jabble Awlia, Rabak, Khashim Elgirba and Algadarif power plants. The single line diagram is obtained after representing each power plant by one equivalent machine and all the transmission lines have been modeled with lumped parameter using the π equivalent, and the double circuits transmission lines are reduced to equivalent lines. All per unit values are referred to a power base of 1000 MVA. The NEPLAN Software Version 5.5.8 used to conduct study the static voltage stability analysis. The proposed method is tested under normal operation with and without including the SVC. The results are showing in Tables and Figures below.

4.1 Case 1 system without SVC

Figure 2 shows the single line diagram of Sudanese national grid before installation of SVC. Figure 3 shows the voltage profile of the system buses from the load flow of all substations. It can be seen that from this figure, all nodal voltages are within accepted limits (0.95 – 1.05) pu.

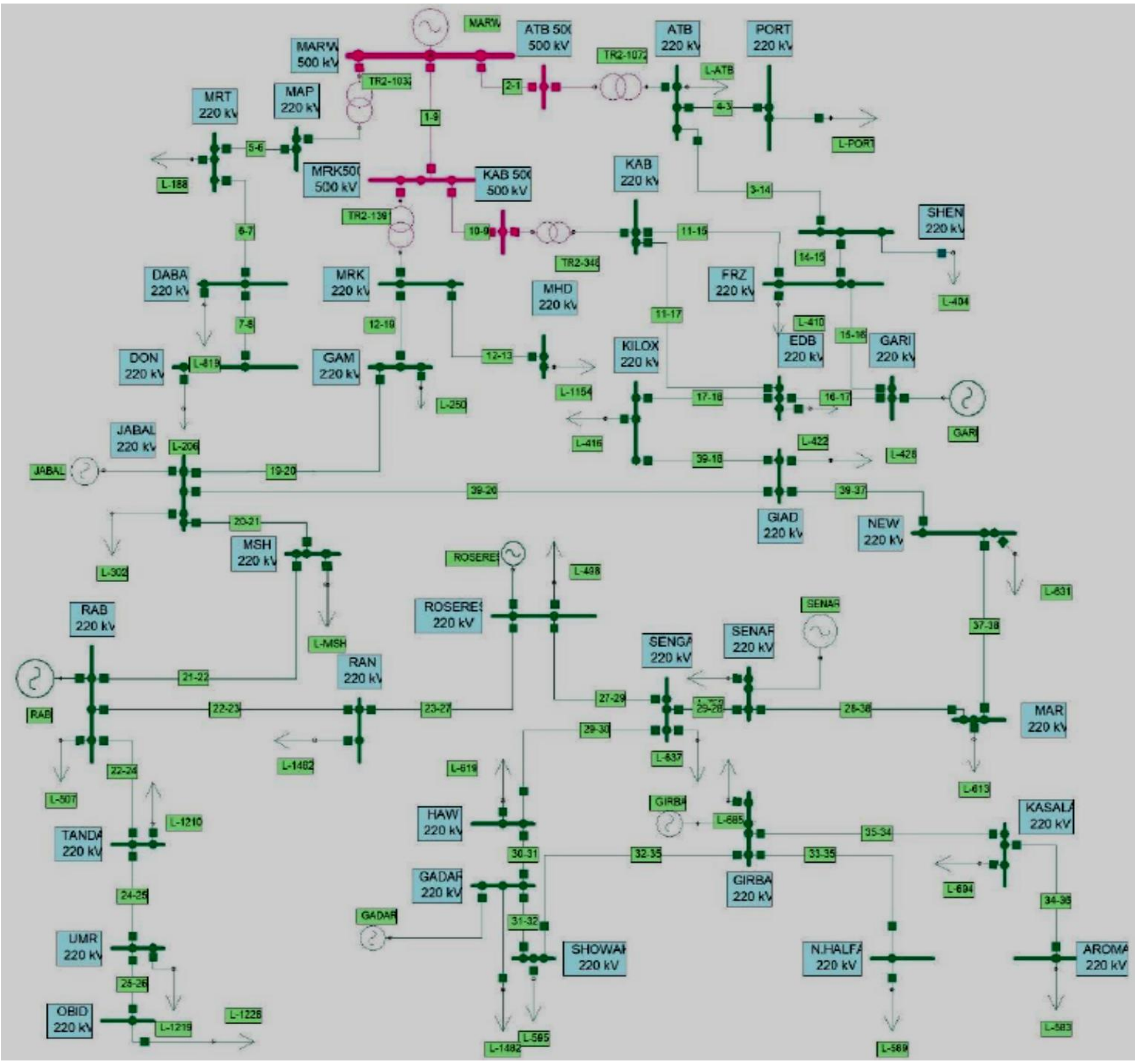
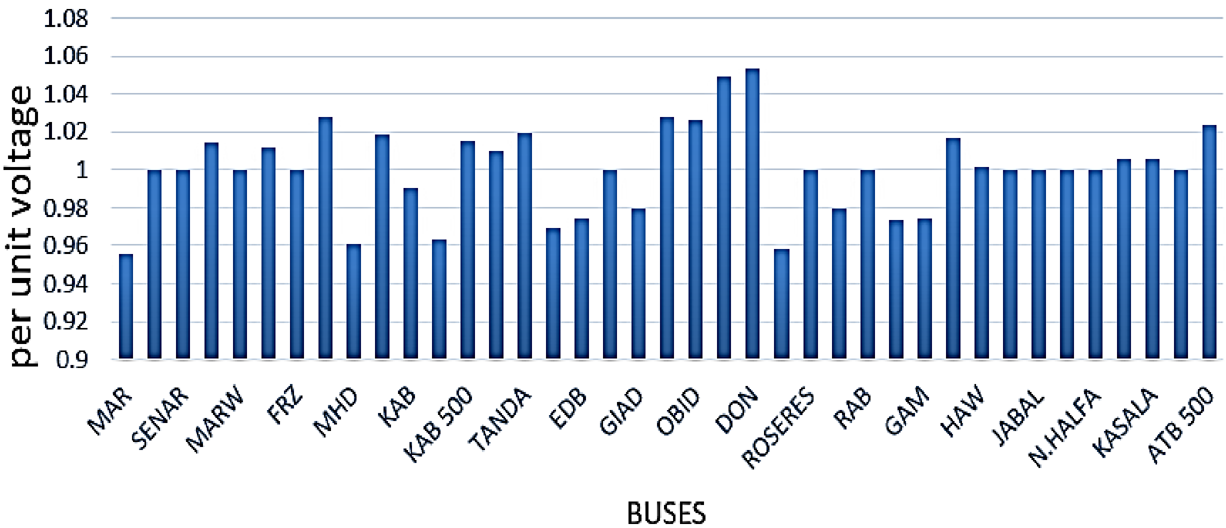
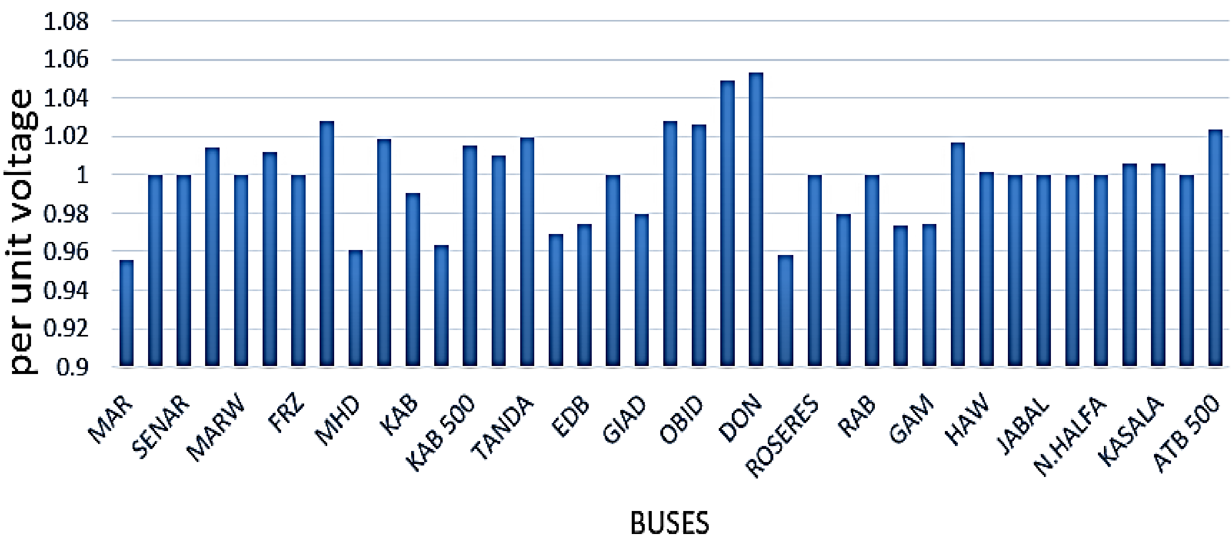


Figure 2: Single Line Diagram for Sudanese National Grid

Figure 4 provide the results of the V-Q Sensitivity. We can observe that all buses have positive V-Q sensitivity, that means the system is stable. The buses that have the largest values of V-Q sensitivity are considered as the weakest buses which they need to improvement. Further, Figure 4 shown that the five weakest substations are PORT, Dongola, Obeid, Daba, Umrawaba which have a largest V-Q sensitivity.


per unit voltage
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
MAR
SENAR
MARW
FRZ
MHD
KAB
KAB 500
TANDA
EDB
GIAD
OBID
DON
ROSERES
RAB
GAM
HAW
JABAL
N.HALFA
KASALA
ATB 500
BUSES


per unit voltage
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
MAR
SENAR
MARW
FRZ
MHD
KAB
KAB 500
TANDA
EDB
GIAD
OBID
DON
ROSERES
RAB
GAM
HAW
JABAL
N.HALFA
KASALA
ATB 500
BUSES

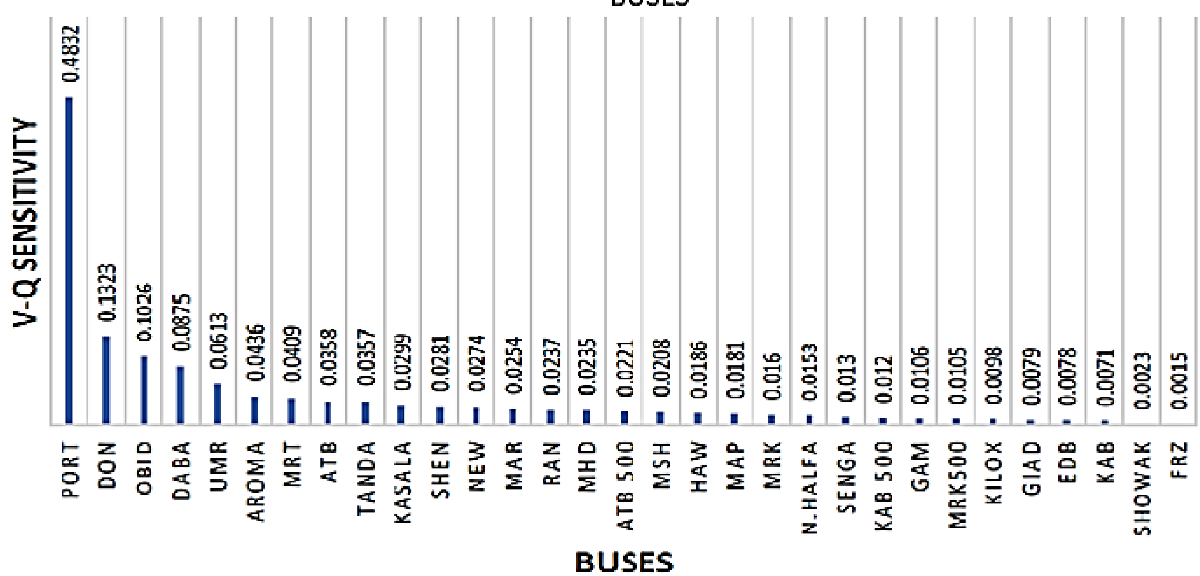

V-Q SENSITIVITY
0.4832
0.1323
0.1026
0.0875
0.0613
0.0436
0.0409
0.0358
0.0357
0.0299
0.0281
0.0274
0.0254
0.0237
0.0235
0.0221
0.0208
0.0186
0.0181
0.016
0.0153
0.013
0.012
0.0106
0.0105
0.0098
0.0079
0.0078
0.0071
0.0023
0.0015
PORT
DON
OBID
DABA
UMR
AROMA
MRT
ATB
TANDA
KASALA
SHEN
NEW
MAR
RAN
MHD
ATB 500
MSH
HAW
MAP
MRK
N.HALFA
SENGA
KAB 500
GAM
MRK500
KILOX
GIAD
EDB
KAB
SHOWAK
FRZ
BUSES

Figure 3: Voltage Profile of the System

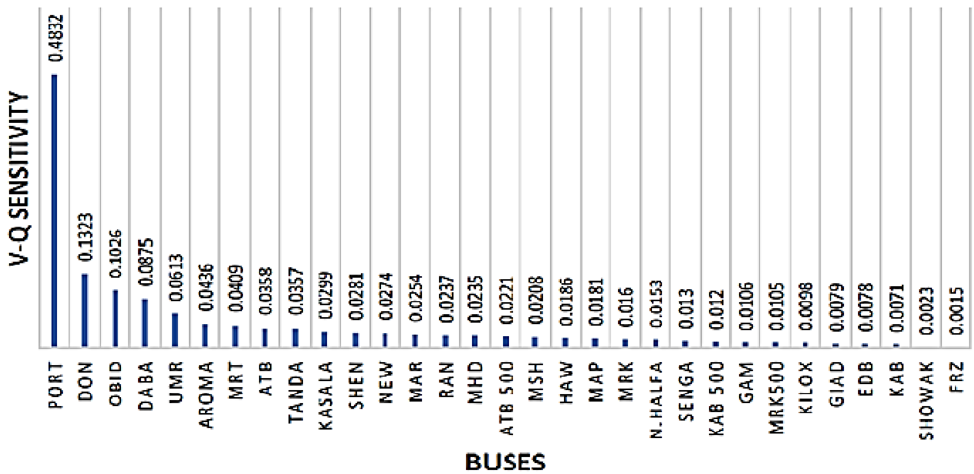


Figure 4: V-Q Sensitivity Analysis for Base Case

4.2 Case 2 System with SVC

To improve the voltage level in different buses in power system so as to be equal to the nominal value (i.e. 1 pu), we need to installing some SVC at the weakest buses. In this case we installed SVC at Daba, Dongola, Markhyat 220, Obeid and Port Sudan.

Table 1 and Figure 5 shows the comparison between the voltage level at the busses before and after SVC including. The result shows that all buses which including SVC, the voltage level is become at nominal value 1.0 per unit. Figure 5, represents the voltage level at the buses which the SVC is installed.

Table 1: bus voltage level at SVC placed

Bus name	Before SVC	After SVC
Markhyat	1.0142	0035
Port	0.9631	1.0
Dongola	1.0495	1.0
Daba	1.0537	1.0
Obeid	1.0264	1.0
Umrawaba	1.0276	1.0

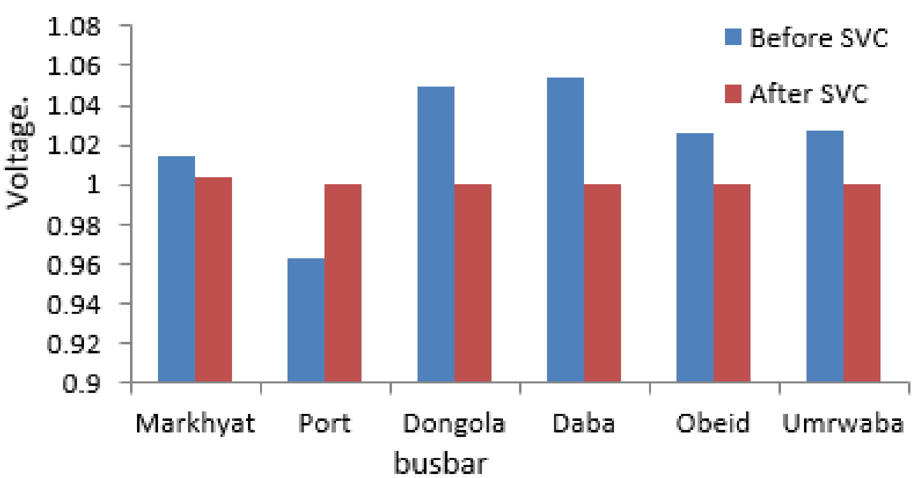


Figure 5: Bus Voltage Level at SVC Placed

Table 2 and Figure 6 shows the results of load flow for the bus voltage in per unit before and after installation the SVC. It can be seen that some of buses are improved, for example, Tandalty and Umrawaba, which at the same line of Obeid.

Table 2: Bus Voltage after using SVC

Bus name	**oltage p.u ithout SVC**	**Voltage .u with SVC**	**Bus name**	**oltage p.u thout SVC**	**oltage p.u ith SVC**
MAR	0.956	0.9561	UMR	1.0276	1.00
SENGA	1.00	1.00	OBID	1.0264	1.00
SENAR	1.00	1.00	DABA	1.0495	1.00
MAP	.0142	1.0035	DON	1.0537	1.00
MARW	1.00	1.00	NEW	0.958	0.9581
SHENDI	.0115	1.0134	ROSERES	1.00	1.00
FRZ	0.9996	0.9997	MSH	0.9794	0.9794
MRT	.0275	1.0038	RAB	1.00	1.00
MHD	0.9608	0.9608	MRK	0.9736	0.9736
MRK500	.0188	1.0189	GAM	0.9747	0.9747
KABASHI	0.9903	0.9903	ATB	1.0167	1.0207
PORT-SUDAN	0.9631	1.00	HAW	1.0013	1.0013
KAB 500	.0153	1.0153	GADAR	1.00	1.00
RANK	.0104	1.0104	JABAL	1.00	1.00
TANDA	.0194	1.0032	HOWAK	1.0002	1.0002
KILOX	0.9697	0.9698	N.HALFA	0.9995	0.9995
EDB	0.9747	0.9747	AROMA	1.0059	1.0059
GARI	1.00	1.00	KASALA	1.0056	1.0056
GIAD	0.9793	0.9793	GIRBA	1.00	1.00
			ATB 500	1.0234	1.0253

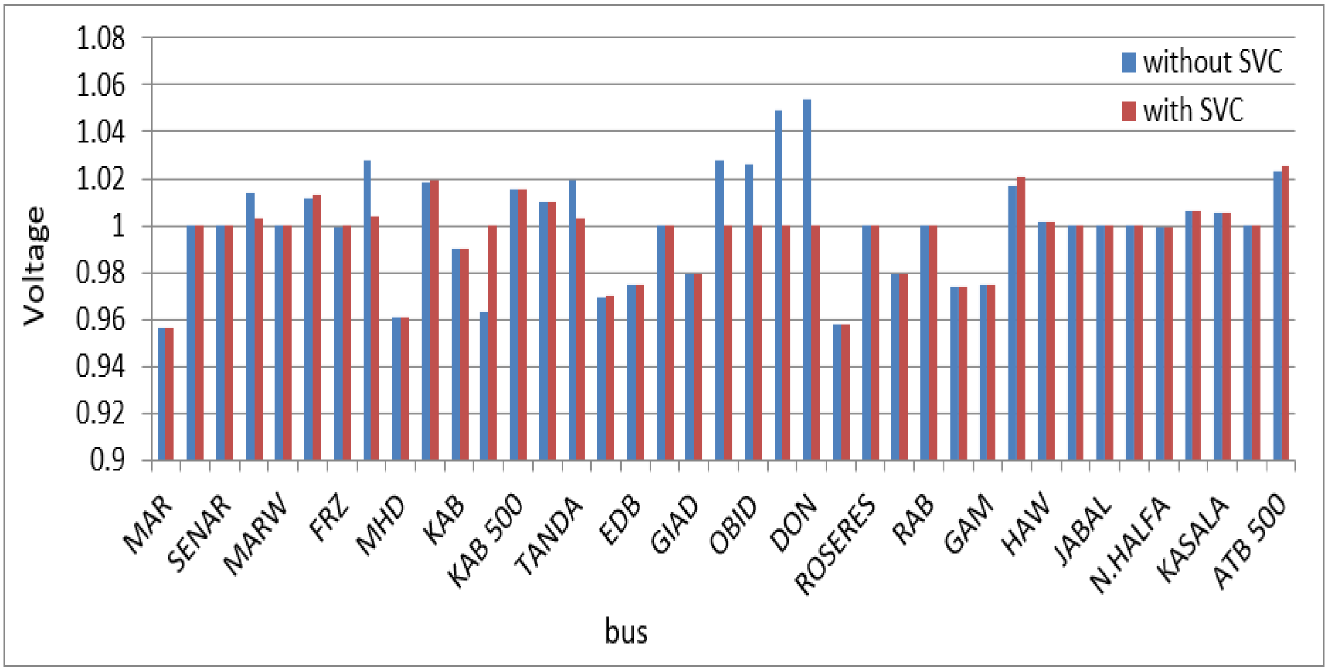


Figure 6: Bus Voltage before and after installing SVC

5. Conclusion

Voltage stability and the risk of collapse have become significant challenges in modern power systems, especially in deregulated markets where systems operate at maximum capacity. This heightened stress makes systems vulnerable to outages and disturbances, necessitating an analysis of their response to prolonged overloads and unexpected disruptions.

Voltage stability is defined as a power system's ability to maintain voltage levels amid increasing load and power demand, while voltage collapse refers to the widespread loss of voltage resulting from instability. Voltage security involves not only stable operation but maintaining stability after reasonable contingencies. Disturbances such as increased load or transmission line outages can trigger rapid or gradual voltage declines, compounded by failures in automatic control systems. These voltage drops can occur within seconds to minutes, highlighting the need for vigilant monitoring and management.

Significant blackouts in 2003, including a cascading failure in the Northeast United States and Canada affecting over 50 million people, as well as major incidents in Sweden, Denmark, and Italy, illustrate the critical impact of disturbances and the role of both fast- and slow-acting devices on voltage stability.

This paper proposes a method to enhance voltage stability in Sudan’s national grid through the optimal placement of Static VAR Compensator (SVC) controllers. The study shows that V-Q sensitivity can effectively pinpoint the weakest bus in the system, enabling voltage stability improvement by minimizing the voltage stability index and lowering generation costs through reactive power injection at the identified bus.

Reference

[1] Ayat Y. Elshreef1, Ibrahim H Mho, Kamal R. Doud.' Improvement of the Under-Voltage Problem in the Sudanese Network by Using FACTS-SVC Controller' 2021
[2] B.R GUPTA "Power system Analysis and Design" 2008
[3] Sidnei do Nascimento and Maury M. Gouvêa Jr." Voltage stability enhancement in power systems with automatic facts device allocation" 3rd International Conference on Energy and Environment Research, ICEER, Barcelona, Spain, 2017
[4] Mahmood Kh Zarkani, Ahmed S. Tukkee, Mohammed. J Alali" Optimal placement of facts devices to reduce power system losses using evolutionary algorithm" Indonesian Journal of Electrical Engineering and Computer Science Vol. 21, No. 3, March 2021, pp. 1271~1278
[5] Mohammed, O, Hassan. Abdelkareem I, Idrees, Mustafa E. Hassan. "Static voltage Stability Assessment of Sudan National Electric Grid (SNEG) Through Optimal Placement of SVC" International Journal of Advanced Research in Science, Engineering and Technology Vol. 6, Issue 7 , July 2019
[6] Nithin A Skaria, Sarin Baby, Anumodu D.M." Optimal Placement of SVC in Power System for Voltage Stability Enhancement Using Genetic Algorithm" International Journal of Emerging Trends in Science and Technology, vol. 1, no. 9, pp 1452-1462, 2014.
[7] IEEE/CIGRE Joint task force report on, "Definition and classification of power system stability", IEEE Transaction on Power Systems, Vol. 19, pp. 1387-1401, 2004.
[8] CIGRE WG 38.02 Task force No.10, "Modeling of voltage collapse including dynamic phenomena", Technical report of task force 38.02.10, draft 3, CIGRE, June 1992.
[9] D. Novosel, M. M. Begovic and V. Madani, "Shedding light on blackouts", IEEE Power and Energy Magazine, Vol. 2, No.1, pp. 32-43, Jan/Feb 2004.
[10] J. Bialek, "Are blackouts contagious?", IEE Power Engineer, pp. 10-13, Dec/Jan, 2003/04.
[11] C. W. Taylor, "Power system voltage stability", New York: McGraw-Hill, 1994.
[12] P. Kundur, "Power system stability and control", New York: McGraw-Hill, 1994.
[13] T. V. Cutsem and C. Vournas, "Voltage stability of electric power system", Norwell, MA: Kluwer, 1998.
[14] Salha Ali Al Disi, "voltage stability assessment of Dubai power grid using a detailed load model", Sharjah, United Arab Emirates, vol. 2, No.4, pp 1-150, June 2013.
[15] G.K. Morison, B. Gao, P. Kundur, "Voltage Stability Analysis using Static and Dynamic Aproaches," IEEE Transactions on power system, vol. 8, no. 3. Pp. 1159 – 1170, August1993.
[16] A.S. AlDessi, A.I. Ibrahim, A. H. Osman," A comprehensive Methodology for Voltage stability Assessment of power system using Model Analytical Tools" 3rd International Conference on Electric Power and Energy Conversion system (EPECS) Sharjah 2011
[17] BhawanaTelang, Prabodh Khampariya," Voltage stability Evaluation Using Model analysis" International Journal of Scientific Research Engineering & Technology (IJSRET), Volume 4, no. 4, pp408-4011, April 2015.
[18] Abdelrahman Ali Karrar, Elfadil Zakaria Yahia," Voltage stability evaluation in Sudan National grid", Sudan Engineering Society Journal, Volume 54, No.51, pp924, September 2008