ISSN: 2350-0328

International Journal of Advanced Research in Science, Engineering and Technology

Vol. 6, Issue 7 , July 2019

Static voltage Stability Assessment of Sudan National Electric Grid (SNEG) Through Optimal Placement of SVC

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ABSTRACT: There are several techniques and tools used to investigate voltage stability problem of a power system, in this paper two methods of analysis are used, V-Q sensitivity and modal analysis. Flexible AC transmission system (FACTS) compensators are a recent emerging technology that can helps in improving the static, and dynamic performance of power system, but these compensators needs to be placed optimally in a power system. In this paper the static VAR compensator (SVC) is implemented to enhance static voltage stability. Active power index (VPI-bus), Reactive power index (VQI-bus) and line index (L-index) are used to determine the best location of SVC. These indices are described and applied to the Sudan National Electric Grid (SNEG). Simulation results proved the effectiveness of SVC on the voltage stability enhancement.

KEY WORDS: SVC, Modal analysis, V-Q sensitivity analysis, Active power index(VPI-bus), Reactive power index(VQI-bus), Line index(L-index).

I.INTRODUCTION

Majority of power systems now days are operated under stressed conditions, then were usual in the past. Environmental pressure on transmission expansions, exponentially growing demands and penetration of new types of loads at demand side are some of the responsible factors for these stressed conditions. Under certain conditions, voltage instability may escalate to a form of voltage collapse, which intimidates system security [1]. A system is voltage unstable if only one bus in the system is unstable, voltage instability phenomenon is generally characterized as an inadequate VAR support at critical system buses [2]. Voltage instability results ina several voltage collapses of networks in some cases, rotor angles and frequency remained constant, while voltage continued to decline to a critical value, causing protection equipment to isolate the network. In other cases, rotor angles and the frequency swings accompanied the voltage decay [3].

In this paper two methods of analysis are used, V-Q approach, which illustrates the sensitivity and changes of bus voltage with respect to reactive power absorption or injections? FACTS compensators are used to minimize voltage instability issues [4]. In this paper, SVC is proposed to improve voltage stability, optimal allocation of SVC is selected by using active power index, reactive power index and line stability index, and all approaches are based on a relative change in the bus voltages deviating from an initial operating condition to the voltage stability limit [5].

A. LITERATURE SURVEY

Voltage instability in power systems has become a challenging issue for the operators and planners due to the growth and expansion of power system networks, ref [6] presents main definitions and classifications of power system, in [7] concepts and effect of reactive power control on voltage stability is explained. Different techniques are applied to assess the voltage stability are proposed in [8-11]. to increase the system capacity, and the efficiency of power system from voltage stability view point,FACTS Controllers are proposed in [12-14]. An advanced technique of placing and sizing of FACTS controllers is addressed in [15, 16].

The paper is arranged as follows, section 2 discusses voltage stability tools and techniques; section 3 discusses svc modelling and characteristics; section 4 discuss the optimal location of SVC; section 5 describes the case study system details; in section 6a detailed discussion and results are presented, conclusion is given in last section.

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International Journal of Advanced Research in Science, Engineering and Technology
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II. VOLTAGE STABILITY TOOLS AND TECHNIQUES

There are two methods used for voltage stability analysis; dynamic analysis, and static analysis. Dynamic analysis is based on a linearized dynamic model of a power system, followed by a nonlinear simulation .Static analysis solves a steady-state power flow equation ,it solves only the algebraic equations.It is computationally more efficient compared with dynamic approach. Therefore, static analysis is suitable for voltage stability studies of the bulk systems in which voltage stability limits for many pre-contingency and post contingency cases must be determined.

A. Q Sensitivity Analysis

This technique calculates the relationship between voltage change and reactive power changes at different buses using reduced Jacobian matrix [17].
Linearized power flow equation can be expressed as:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}J_{P\theta} & J_{PV}\\ J_{Q\theta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \quad \ldots\ldots (1)$$

Where:ΔP=incremental change in real power ΔQ=incremental change in reactive power, $\Delta\theta$= incremental change in bus voltage angle, ΔV=incremental change in bus voltage magnitude
Let ΔP=0. Then:
Where:$J_R=\left[J_{QV}-J_{Q\theta}J_{P\theta}^{-1}J_{PV}\right]$……………… (2)
$J_R$is the reduced Jacobin Matrix of the system form equation (3), then:
$\Delta V=J_R^{-1}\Delta Q$ ……………….(3)
A positive V-Q sensitivity indicates stable operation; the smaller positive sensitivity, the system is more stable. As stability decreases when the magnitude of the sensitivity increases.Negative V-Q sensitivity indicates unstable operation.

B. Modal Analysis

Voltage stability characteristics of a system are determined by calculating eigen values and eigenvectors of the reduced Jacobian Matrix given by the equation [18].

$$J_R=\xi\eta\Lambda \quad \ldots\ldots (4)$$

Where: ξ = Right eigenvector matrix of J_R, η = Left eigenvector matrix of J_R, Λ= Diagonal eigenvector matrix J_R
Where:$J_R=\left[J_{QV}-J_{Q\theta}J_{P\theta}^{-1}J_{PV}\right]$ ……………… (5)

AndJ_R is the reduced Jacobian matrix. We can write:

$$\Delta V=J_R^{-1}\Delta Q \quad \ldots\ldots (6)$$

From the above equation we get:

$$\Delta V=\xi\Lambda^{-1}\eta \quad \ldots\ldots (7)$$

Substitute equation.3 in equation.2 we get

$$\Delta V=\xi\Lambda^{-1}\eta\Delta Q \quad \ldots\ldots (8)$$

$$\Delta V=\sum\left(\xi_i * \eta_i/\lambda_i\right)\Delta Q \quad \ldots\ldots (9)$$

Where:ξ_i is the i^{th} column of right eigenvector &η_i the i^{th}row left eigenvector of J_R. Each eigenvalue λ_i and the corresponding right &left eigenvalue ξ_i&η_i defines the i^{th} mode of Q-V response.

C. Bus Participation Factor

Left and right eigenvectors corresponding to the critical modes in the system can reflect information regarding the mechanism of voltage instability. The bus participation of the bus can be expressed as.

$$P_{ki}=\xi_{ki}\eta_{ki} \quad \ldots\ldots (10)$$

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
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D. Branch participation Factor

Indicates, for each mode, which branches consume the most reactive power in response to an incremental change in reactive load. Branches that have high participations factors, are either weak links or heavily overloaded. From Equation.11 the vector of bus reactive power variations is:

$$V=\Lambda^{-1}q \quad \ldots\ldots (11)$$

$$\Delta Q^{(i)} = \eta^{-1}q = \xi\, q = \xi_i \quad \ldots\ldots (12)$$

Where ξ_i is the i^{th} right eigenvector of J_R assume that all right eigenvector is normalized so that:

$$\sum_j \xi_{ji}^2 = 1 \quad \ldots\ldots (13)$$

With the vector of bus reactive powervariations equal to $\Delta Q^{(i)}$the vector of bus voltage variations, $\Delta V^{(i)}$ is:

$$\Delta V^{(i)} = \frac{1}{\lambda}\Delta Q^{(i)} \quad \ldots\ldots (14)$$

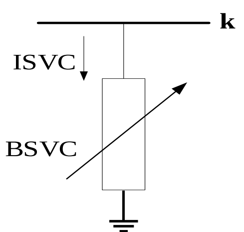
$$\Delta Q^{(i)} = -J_{P\theta}^{-1}J_{PV}\ \Delta V^{(i)} \quad \ldots\ldots (15)$$

Relative participation of branch j in mode i is given by the participation factor:

$$P_{ji} = \frac{\Delta Q_{losses}\ \text{for branch } j}{\text{Maximum } \Delta Q_{losses}\ \text{for all branches}} \quad \ldots\ldots (16)$$

III. STATIC VAR COMPENSATOR (SVC)

SVC is basically a shunt connected static VAR generator that cans exchanges inductive or capacitive current with the power system so as to keep or control specific power variables. SVC is used to control the grid voltage ,if the power system's reactive load is capacitive, SVC will use thyristor controlled reactors to consume VARs from the system, reducing the system voltage. Under inductive conditions, capacitor banks are automatically switched in, thus providing a higher system voltage. SVC is modelled as an ideal reactive power injection at the load ends. Variable shunt susceptance model of SVC is shown in Fig.1



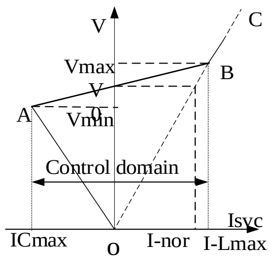


Figure 1: Schematic Diagram of SVCFigure 2: V-I characteristics of SVC

Then the current drawn by the SVC is:

$$I_{SVC} = jB_{SVC}V_k \quad \ldots\ldots (17)$$

Reactive power drawn by the SVC, which is the same reactive power injected at bus k.

$$Q_{svc} = -V_k^2 B_{svc} \quad \ldots\ldots (18)$$

Where: B_{svc}= The susceptance of SVC, V_k = The voltage at bus k.

Steady-state operating region of the SVC is split into three sub-regions as shown in figure.2; A linear control region, in which the voltage control system is provided with appropriate reactive power resources, and the set-point can be defined anywhere on the AB characteristic. This region is bounded by the reactive power Q_{Cmax}, supplied by the capacitors, and by the reactive power Q_{Lmax} absorbed by the reactor, that is $Q_{Cmax} \leq Q \leq Q_{lmax}$ [19].

In practice, a SVC implement droop control of the voltage at the regulated bus, with a slope of about 5%. High voltages region (BC), resulted from the limitation in the inductive reactive power, i.e. Q >Q_{Lmax}. In other words is out of the control area(behaves like a fixed inductive susceptance). Low voltages region (OA), resulted from the limitation in the capacitive reactive power, i.e. Q <Q_{cmax}. SVC, in other words is out of the control area and (behaves like a fixed capacitive susceptance).

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International Journal of Advanced Research in Science, Engineering and Technology
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IV. OPTIMAL LOCATION OF SVC

Three indices are proposed, toinvestigate voltage stability problem based on bus and line power system:

A- Active power index (VPI_{bus})

Relates voltage profiles and maximum power transfer in power system. The active power index has a maximum value of 1 if the system is about to suffer a voltage collapse and minimum value of 0 when there is no load on the system.

$$VPI_{bus} = \frac{4P_j}{diag\ (|G_{bus}|)|V_i|^2} \leq 1.0 \qquad (19)$$

B- Reactive power index (VQI_{bus})

Establish the relationship between voltages and load reactive powers. $VPI_{bus}$and VQI_{bus}vary from zero to one indicating system stability boundaries. If values of $VPI_{bus}$and VQI_{bus}close or near to the unity, the voltage stability reach stability limits. Voltage collapse occurs when both $VPI_{bus}$and $VQI_{bus}$are exceeding their stability limits [20].

$$VQI_{bus} = \frac{4Q_j}{diag\ |B_{bus}||V_i|^2} \leq 1.0 \qquad (20)$$

C-Line stability index (L-index)

L-index is varying from zero to one,once the value of L- indexapproach unity, the voltage stability reaches stability limits. The occurrence of voltage collapse is taken place once L-indexexceeding their stability limits. [21].

$$L\ (p.u) = 4\left\{\left(\frac{PX-RQ}{V_s^2}\right)^2 + \left(\frac{RP+XQ}{V_s^2}\right)\right\} \qquad (21)$$

V. CASE STUDY

A simplified transmission network of Sudan National Grid consists of four 500kV substation and thirty-five 220kV substations are shown in figure 3. This single line diagram is obtained after representing each power plant by one equivalent machine and all the transmission lines have been modelled with lumped parameter using the πequivalent and the double circuits transmission lines are reduced to equivalent lines. All per unit values are referred to a power base of 1000 MVA.

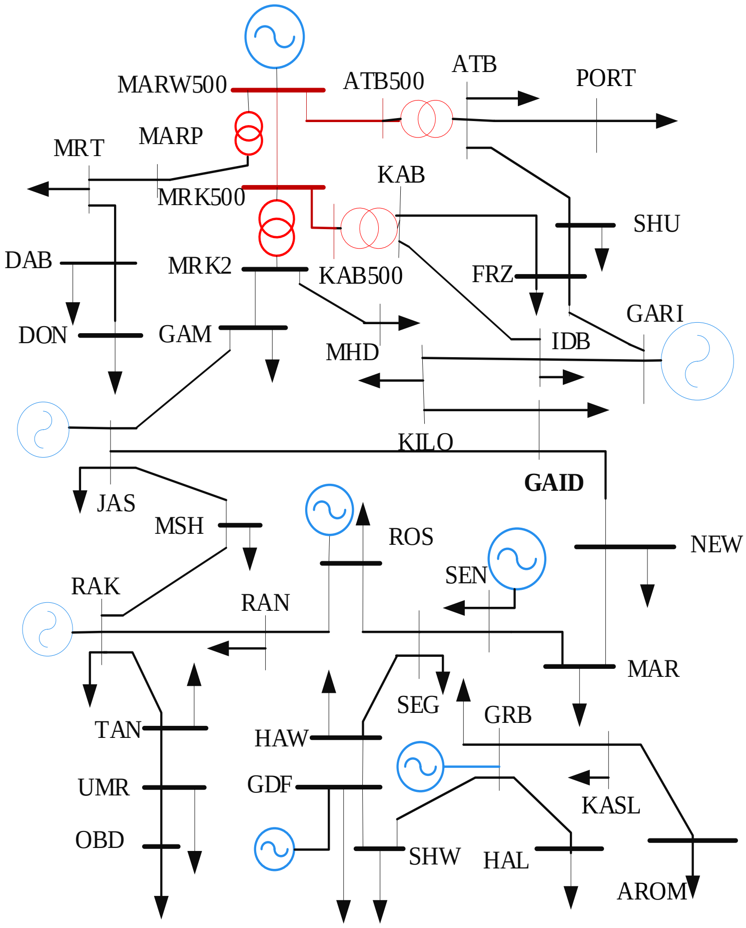

Figure 3: single line diagram of system

VI.RESULTS AND DISSCUSSION

The simulation of Network is carried out at Base case and Critical Case. Table 1 provide the results of V-Q Sensitivities at two cases, it is seen that the buses that have the largest values of self V-Q sensitivities are considered as the weakest buses that need improvement of voltage stability margin,by reduction of their sensitivities. Table 1, also shows that the weakest buses in the system are PORT, ATB and DONG. Figure 4 and 5 show the weakest bus in the system is port Sudan.

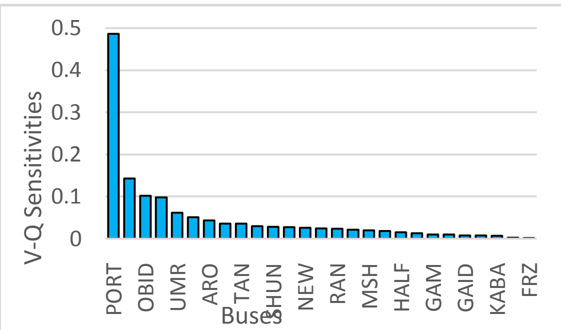

Figure 4: V-Q Sensitivity for Base Case

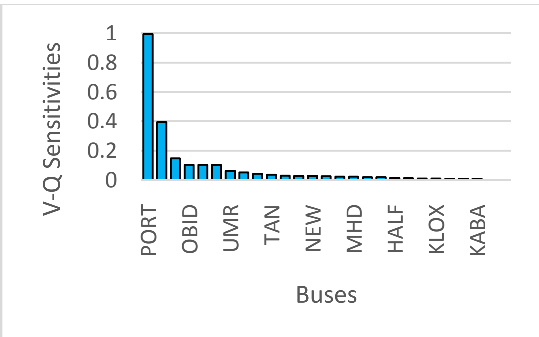

Figure 5: V-Q Sensitivity for Voltage Stability limit.

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International Journal of Advanced Research in Science, Engineering and Technology
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Table 1: V-Q Sensitivities at Base and Critical Case.

Base Case		Critical Case		Base Case		Critical Case	
Bus	V-Q Sens	Bus	V-Q Sens	Bus	V-Q Sens	Bus	V-Q Sens
PORT	**0.4857**	PORT	**0.9928**	MAR	0.0243	MAR	0.0249
DON	**0.1431**	ATB	**0.3947**	RAN	0.0235	RAN	0.0235
OBID	0.1019	DON	0.1485	MHD	0.0215	MHD	0.0233
DAB	0.0977	OBID	0.1046	MSH	0.0199	MSH	0.0198
UMR	0.0612	SHU	0.1041	HAW	0.0184	HAW	0.0185
MAT	0.0506	DAB	0.1011	HAF	0.0153	HAF	0.0153
ARO	0.0434	UMR	0.0624	SEG	0.0129	SEG	0.0129
ATB	0.0357	MAT	0.0518	GAM	0.0101	GAM	0.0106
TAN	0.0357	ARO	0.0436	KILO	0.0098	KILO	0.0102
KASS	0.0299	TAN	0.0362	GAID	0.0078	IDB	0.0081
SHU	0.028	KASS	0.03	IDB	0.0078	GAID	0.008
MAP	0.0274	MAP	0.0277	KAB	0.0071	KAB	0.0073
NEW	0.0262	NEW	0.0269	SHW	0.0023	SHW	0.0023

Table 2 illustrates results of Model Analysis for the Buses at different Eigenvalues. Buses that have highest eigenvector components as well as highest participation factors are considered as weakest buses, it is can be seen that, buses PORT, ARO and OBD have highest participation factor which mean they are weakest buses in the system at two cases. Figure 6, 7 show that the weakest buses are PORT-Sudan, AROMA, OBD, DONGLA and ATBARA at base case and critical case.

Table 2: Model Analysis for Base case and Critical Case.

Base case		Critical case		Base case		Critical case	
Bus	P- Factor	Bus	P- Factor	Bus	P- Factor	Bus	P- Factor
POR	**0.9791**	POR	**0.9838**	TAN	0.1328	MRT	0.1226
ARO	**0.6103**	ARO	**0.6104**	MRT	0.1238	GAM	0.0831
OBD	**OBD**	OBD	**0.5543**	NEW	0.1013	MAP	0.0413
DON	**0.4967**	DON	**0.4986**	MAR	0.0825	NEW	0.0313
ATB	**0.465**	ATB	**0.4546**	GAM	0.0756	MAR	0.0245
KAS	0.3897	KAS	0.3896	MAP	0.042	MRK	0.0152
DAB	0.3375	DAB	0.3374	KLO	0.0137	KAB	0.012
UMR	0.3153	UMR	0.314	KAB	0.0132	KLO	0.0098
MHD	0.2914	SHU	0.2597	IDB	0.0115	IDB	0.009
SHU	0.2859	MHD	0.0211	GAID	0.0105	GAID	0.0048
MRK	0.204	TAN	0.1317				

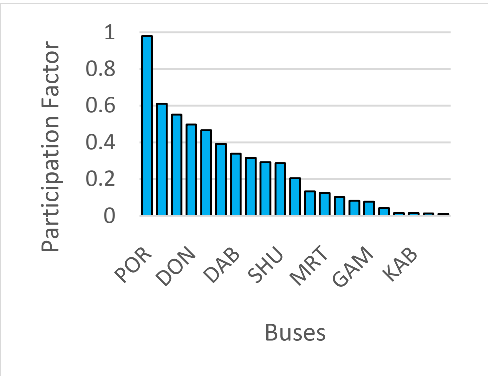

Figure 6: Model analysis for Base Case

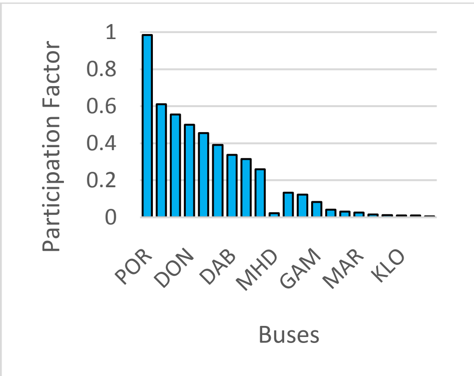

Figure 7: Model Analysis for voltage stability limit.

ISSN: 2350-0328

International Journal of Advanced Research in Science, Engineering and Technology

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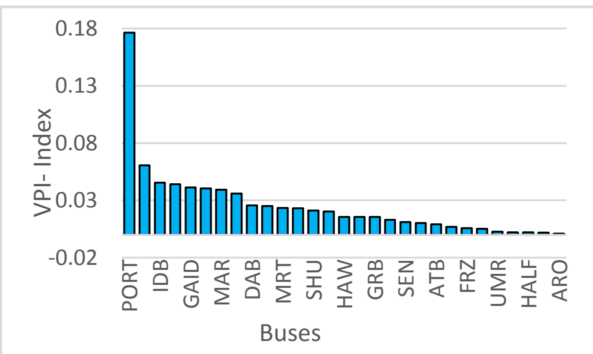
Table 3 illustrate the active power index at the Base Case and Critical Case. The bus that has highest value of the active power index represent weakest bus in the system, it is observed that the buses PORT, GAM IDBA and KILOX are the weakest buses at two cases. Figure 8 represents VPI-bus index method for base case and figure 9 represents the active power index (VPI-bus) at voltage stability limit, it is observed that for both case the weakest buses are PORT, GAMOEIA, IDBA, KILOX, MAR and GAID respectively.

Table 3: Active Power Index at Base case and critical Case

Base Case		Critical Case		Base Case		Critical Case	
Bus	**VPI-bus**	**Bus**	**VPI-bus**	**Bus**	**VPI-bus**	**Bus**	**VPI-bus**
POR	**0.1763**	POR	**0.2714**	MHD	0.0156	MRT	0.0188
GAM	**0.0606**	GAM	**0.0882**	GER	0.0155	OBD	0.0182
IDB	**0.0456**	IDB	**0.0625**	OBD	0.013	SEN	0.0155
KLO	0.044	KLO	0.0624	SEN	0.0112	GDF	0.014
GAID	0.0413	MAR	0.059	GDF	0.0102	ATB	0.0136
MSH	0.0406	GAID	0.0589	ATB	0.0092	DAB	0.0098
MAR	0.0393	MSH	0.0557	TAN	0.0069	TAN	0.0095
JAS	0.0359	JAS	0.0527	FRZ	0.0057	FRZ	0.0083
DAB	0.0257	SHU	0.0327	KAS	0.0053	KAS	0.0073
DON	0.0251	NEW	0.0325	UMR	0.0028	UMR	0.0039
MRT	0.0234	DON	0.0318	RAN	0.0021	RAN	0.0029
NEW	0.0232	SEG	0.0278	HAL	0.0021	HAL	0.0029
SHU	0.0212	MHD	0.0227	SHW	0.002	SHW	0.0027
SEG	0.0203	HAW	0.0215	ARO	0.0012	ARO	0.0017
HAW	0.0157	GER	0.0212				



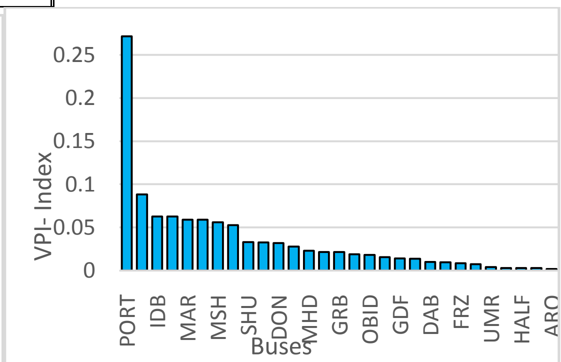


Figure 8: VPI- index method for Base Case.Figure 9: VPI- index method for Voltage stability limit.

Table 4 shows the results of reactive power index where the load of the system is gradually increased from base load until the load flow equation diverged. This is the maximum power that a system can supply before voltage instability happened, it is observed that the buses PORT, MAR, GAID and IDB have highest value of the reactive power index. This mean that they are weakest buses in the system. Figure10 and 11 show the bus reactive power index versus the bus number; where figure 10 represents the VQI-bus index at the Base case, it is observed that the weakest buses at base case and critical case are Port Sudan, Marngan, Giad, Eidbabeker respectively. These buses need improvement of voltage stability margin by reduction of their reactive power index.

Table 4: Reactive Power index for Base Case and critical case.

Base Case		Critical Case		Base Case		Critical Case	
Bus	**VQI-bus**	**Bus**	**VQI-bus**	**Bus**	**VQI-bus**	**Bus**	**VQI-bus**
POR	**0.3875**	POR	**0.5965**	GRB	0.0339	OBD	0.0418
MAR	**0.1741**	MAR	**0.297**	SEG	0.0334	TAN	0.0372
GID	**0.1402**	GID	**0.2614**	OBD	0.0299	DAB	0.0347
IDB	**0.14**	IDB	**0.1918**	TAN	0.0272	HAW	0.0324
GAM	0.1192	GAM	0.1736	HAW	0.0236	SEN	0.032
KLO	0.1116	KLO	0.1584	SEN	0.0233	KSL	0.0204

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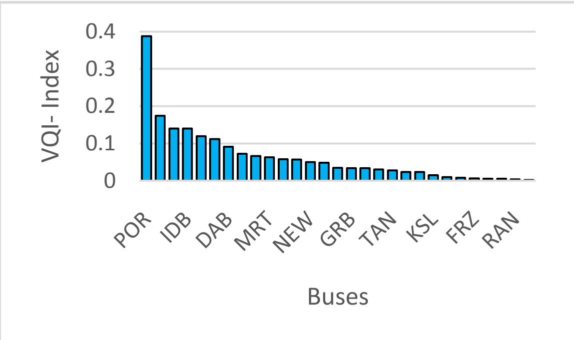
DAB	0.0911	MSH	0.0985	KSL	0.0149	UMR	0.0128
MSH	0.0719	JAS	0.0974	UMR	0.0092	GDF	0.0112
JAS	0.0664	SHU	0.0883	GDF	0.0082	FRZ	0.0091
MRT	0.0629	ATB	0.0828	FRZ	0.0062	HAL	0.008
SHU	0.0574	NEW	0.0693	HAL	0.0056	SHW	0.0075
ATB	0.0563	DON	0.0614	SHW	0.0055	RAN	0.0047
NEW	0.0495	MHD	0.0502	RAN	0.0034	MRT	0.0038
DON	0.0485	GRB	0.0464	ARO	0.0019	ARO	0.0027
MHD	0.0345	SEG	0.0458				



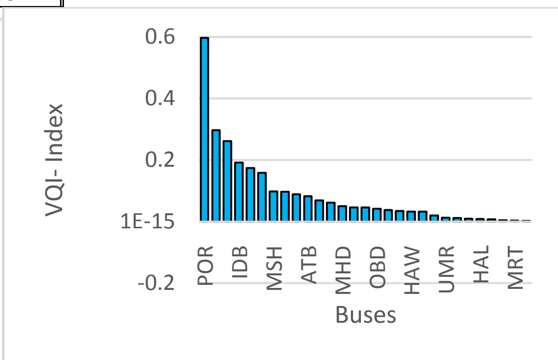


Figure10: VQI-index at Base case. Figure 11: VQI-index for voltage stability limit.

Table 5 illustrate the results of the L-index for the system at the Base case and the critical case for first 10 lines, it is observed that the Lines (ATB-PORT), (GARI-IDB), (SEN-MAR) (NEW-MAR), (MRK-GAM) are the weakest lines which connected to the weakest buses, this mean that they have maximum power that can be flowing before voltage instability occurred, there are suitable location for static VAR compensator to improve power system stability.

Table 5: The Line Index for Base case and Critical Case.

Base case			Critical Case			Base case			Critical Case		
F	**To**	**Lindex**	**F**	**To**	**Lindex**	**F**	**To**	**Lindex**	**F**	**To**	**Lindex**
ATB	POR	**0.6893**	ATB	POR	**1.165**	MRT	ATB	0.0699	MRT	ATB	0.1003
GAR	IDB	**0.1555**	GAR	IDB	**0.216**	DAB	DON	0.0678	JAS	MSH	0.0938
SEN	MAR	**0.1317**	SEN	MAR	**0.2**	JAS	MSH	0.0676	MRK	MHD	0.075
NEW	MAR	**0.091**	NEW	MAR	**0.13**	MRT	DAB	0.0555	KLO	GAD	0.0721
MRK	GAM	0.0901	MRK	GAM	0.1335	MRK	MHD	0.0511	ATB	SHU	0.0677

A Cording to above results three SVC are installed at buses PORT, IDBA and MAR respectively. Because these buses have largest values of indices and the lines connected to these buses are weakest lines (deliver maximum power). It can be observed that the voltage of busses has been improved by implemented SVCs. The results of the system before and after installed SVC are showing in table 6, figure 11 shows the comparison of voltage profile of the system with and without SVC.

Table 6: The Bus voltage magnitude with and without SVC.

No	B. name	B. case	with SVC	No	B. name	B. case	with SVC
1	Atbara-5	1.0184	**1.0209**	9	Shendi	1.0084	**1.0114**
2	Atbara	1.0146	**1.0194**	10	Free zone	0.9999	**1.0014**
3	port Sudan	0.9599	**1**	11	Eidbabiker	0.9762	**1**
4	Markh-5	1.023	**1.027**	12	Kilox	0.9712	**0.9926**
5	Kabashi-5	1.0182	**1.0233**	13	Gamoeia	0.9878	**0.989**
6	Kabashi	0.9932	**1.0057**	14	Newhouse	0.9703	**0.9933**
7	Markhyat	0.9968	**0.9992**	15	Meringan	0.9692	**1**
8	Mahadia	0.9843	**0.9867**	16	Giad	0.9815	**0.9922**

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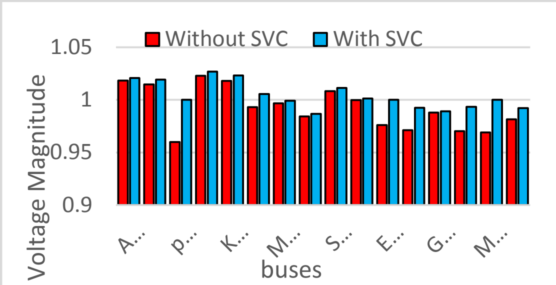

Figure 12: Voltage Profile with and without SVC.

VII.CONCLUSION

Three different voltage stability investigation methods have been used to select the optimal location of FACTS controllers. The line index, active power index and reactive power index are more accurate methods for analysis the voltage stability because they consider suitable location of SVC. The installation of SVC at one or more suitable points in the network can increase transfer capability and give higher transient stability limit while maintaining a smooth voltage profile under different operating conditions.

The results show that the voltage stability is enhanced at buses by considering the objectives such as minimization of voltage stability index, and minimization of generation cost. The SVC capable of increasing static voltage stability margin and improvement the voltage profile by injected reactive power at the weakest bus.

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International Journal of Advanced Research in Science, Engineering and Technology

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