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Enhancing Voltage Stability Limits Using SVC Based Continuation Power Flow Analysis

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Abstract — *this paper outlines continuation power flow method to assess voltage stability of Sudan national grid (Khartoum – 110 kV, 220Kv, and 500 kV level), to identify critical areas of the system. Static VAr Compensator (SVC) is placed at the critical bus in order to improve voltage stability margin and enhance the overall performance. Test system is analyzed at the base case and compensated case using MATLAB power system analysis toolbox (PSAT). A comparison between two cases showed that SVC enhances voltage profile and stability limits of the system.*

Keywords- *Continuation power flow, Voltage stability margin, SVC, PSAT.*

I. INTRODUCTION

Voltage stability is considered to be a principal issue of power system security problems. With the continuing expanding of power system networks and the development of power market mechanism, power system is more frequently forced to operate near critical stability limit, which leads to a lower voltage stability margin of the system. Therefore, it is necessary to investigate voltage stability problem of power system [1].
The voltage status of a bus in the power network depends on the received reactive power from the network. When the system reaches the critical loading point or voltage collapse situation, active and reactive power losses rise extremely. Therefore, the reactive power supply has to be reliable and stable.
Providing sufficient reactive power supply at the optimal location not only reduces the active and reactive losses and enhancing the voltage status, but also solves voltage instability problems. Recent technologies of Flexible AC Transmission Systems (FACTS) controllers added new solutions for voltage instability problem by making the transmission system more flexible and improving safe and secure operation of the system [2- 3].
In this paper, continuation power-flow analysis (CPF) is used to assess the system voltage stability and to find the weakest areas to be compensated by using (SVC) FACTS controller.

II. Continuation Power Flow

Conventional power flow analysis is effective when the systems operates at steady state operation conditions, it experiences divergence problems near the critical loading point and the Jacobian matrix of the system is prone to singularity problem. The continuation power flow analysis solves the problem of jacobian matrix singularity at stability limits, it reformulates the equations of power flow analysis in which that they stay conditioned at all possible scenarios of loading conditions. This provides solutions of power flow equations at stable and unstable operation points [4].
Continuation power flow finds a continuity of power flow analysis for all given change of system loading. An early success was the ability to find a set of solution from a base case up to the critical point [5]. The general precept of the continuation power flow is indeed simple. It uses a predictor corrector scheme.
The mathematical model of CPF is similar to that of a conventional power flow analysis in the basic equations except that there is an additional parameter represents the change in load.

$$F(\theta, V) = \lambda k \quad \text{(1)}$$

Where: $\boldsymbol{\lambda}$ is the load parameter; $\boldsymbol{\theta}$ is the vector of bus voltage angles; **V** is the vector of bus voltage magnitudes; **k** is the vector representing percent load change at each bus. The above set of nonlinear equations described by (1) is solved by specifying a value for λ such that $0 \leqq \lambda \leqq \lambda_{critical}$. $\lambda=0$ represents the base load condition, and $\lambda = \lambda_{critical}$ represents the critical load.
Equation (1) can be rearranged as

$$F(\theta, V, \lambda)=0 \quad \text{(2)}$$

(i) Predictor step

Taking derivatives of both sides of equation (2) with the state variables corresponding to the initial solution, will result in the following set of linear equations:

$$F_\theta\, d\theta + F_v\, dV + F_\lambda\, d\lambda = 0$$

$$[F_\theta \quad F_V \quad F_\lambda]\begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix} = 0 \quad \ldots\ldots (3)$$

The addition of λ in the power flow equation showed a presence of new unknown variable, so, there is need for one additional equation to find the solution of the above problem.
Setting one of the components of the tangent vector to +1 or -1. Equation (3) now becomes.

$$\begin{bmatrix} F_\theta & F_V & F_\lambda \\ & e_k & \end{bmatrix}\begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \quad \ldots\ldots (4)$$

Where e_k is a row vector with all elements equal to zero except for the k^{th} element (corresponding to the continuation parameter) being equal to 1. Initially, the load parameter λ is chosen as the continuation parameter and the correspondent component is set to +1. As the critical load reached, the greatest change parameter will be the voltage. Once the tangent vector is found, the next Solution prediction can be calculated by

$$\begin{bmatrix} \theta \\ V \\ \lambda \end{bmatrix} = \begin{bmatrix} \theta_0 \\ V_0 \\ \lambda_0 \end{bmatrix} + \sigma \begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix} \quad \ldots\ldots (5)$$

Where the subscription "0" identifies the values of the state variable at the start of the predictor step.
The step sizes are set so that a power flow solution exists with the specified continuation parameter. If the solution cannot be obtained for a set step size in the corrector step, the step size must be reduced and corrector step must be recalculated until successful solution is found.

(ii) Corrector step:
In the corrector step, a new equation is added to the main set of equations $F(\theta, V, \lambda) = 0$, that equation specify the continuation parameter state.Thus the new set of equation is

$$\begin{bmatrix} F(\theta, V, \lambda) \\ x_k - \eta \end{bmatrix} = 0 \quad \ldots\ldots (6)$$

In the above x_k is the continuation parameter state variable and η is equal to the expected (predicted) value of x_k.The presence of the added equation specifying x_k makes the Jacobian matrix non-singular at the maximum operation point.
The continuation power- flow analysis can be continued beyond the critical operating point and thus obtain solutions corresponding to the lower portion of the P-V curve.
In continuation power-flow analysis, the element of the tangent represents differential change in the state variables in reaction to a differential change in system load. Therefore, dV elements in a given tangent vector are useful in identifying "weak buses", that is buses which experience large voltage variation in reaction to a change in load.

III. Static VAR Compensator:

Static VAR compensators (SVC)s are shunt connected static machines capable of generating inductive or capacitive reactive power, measured as volt ampere reactive (VAr). The term static is used to denote that, unlike synchronous compensators, SVCs present no rotating components, being based on power electronic devices. The SVC contains a static VAr generator (SVG), which can generate capacitive (leading) or inductive (lagging) reactive currents (6-8). Basic structure and characteristics of a SVC are shown in Figure. 1 and Figure. 2.

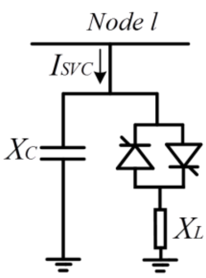

Figure1. Structure of Static Var Compensator

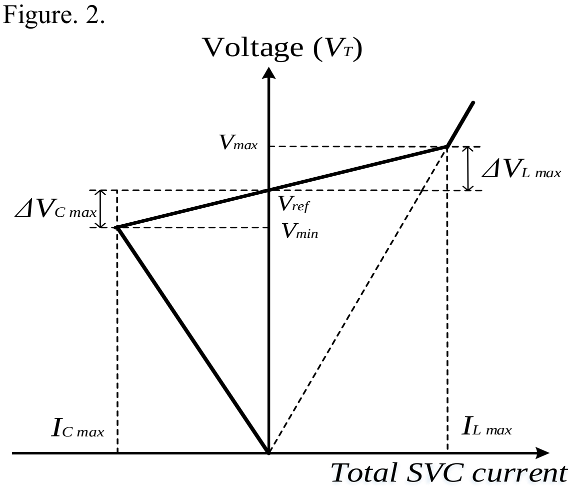

Figure2. Terminal characteristic of Static Var Compensator

Modeling of SVC:
SVC can be modelled as a variable reactance with reactance limits or firing-angle limits. In this paper, SVC modeled as a Shunt variable Susceptance. The equivalent circuit of Figure .3 is used to extract the SVC power equations and the linearized equations required by Newton's method [9].

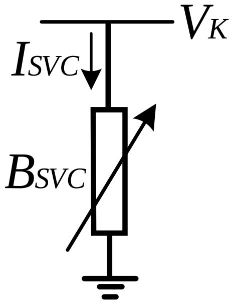

Fig.3. Variable Susceptance model of Static Var Compensator

With reference to Figure 3, the variable shunt compensator admittance equation is, $I_{SVC} = jB_{SVC}V_k$ and the reactive power equation is, $Q_{svc} = -V_k^2 B_{svc}$. The total susceptance B_{svc} is chosen to be the state variable. The linearized equation of the SVC is given by (7), where the susceptance B_{svc} is set to be the state variable.

$$\begin{bmatrix}\Delta P_k \\ \Delta Q_k\end{bmatrix}^i = \begin{bmatrix}0 & 0 \\ 0 & Q_k\end{bmatrix}^i \begin{bmatrix}\Delta\theta_k \\ \Delta B_{svc}/B_{svc}\end{bmatrix} \quad \ldots\ldots (7)$$

At the end of i^{th} iteration, the variable susceptance B_{svc} is updated according to,

$$B_{svc}{}^{i+1} = B_{svc}{}^{i} + \left(\frac{\Delta B_{svc}}{B_{svc}}\right)^i B_{svc}{}^{i} \quad \ldots\ldots (8)$$

The total susceptance of SVC needed to preserve the bus voltage amplitude at the desired value is represented by the changing susceptance of equation (8). Once the compensation scale has been specified, firing angle needed to attain such compensation scale can be calculated.

IV. Case Study

Sudanese national grid (Khartoum – 110 kV, 220kV, and 500 kV level), shown in figure 4 is implemented as study case, it consists of slack bus (Marawy), three generator buses (Gerri, Khartoum north and Jabelawlya) and 26 load buses, all elements connected through 28 transmission lines at three voltage levels (500, 220 and 110 kV). Loads are considered as constant power, and the voltage limits are (0.95 – 1.05) pu. Software used for this study is PSAT.

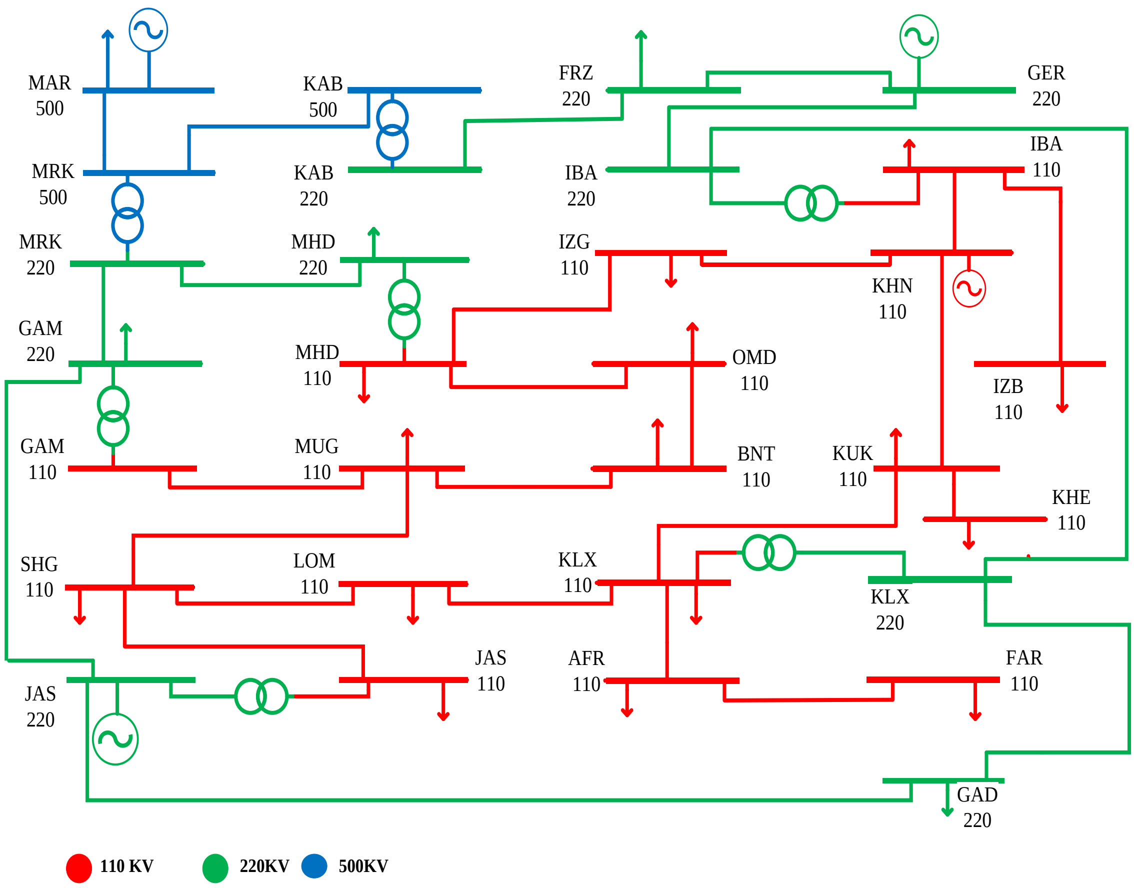

Figure 4: Case study system.

V. Results and Discussions

Two cases are considered, base case without compensation and the compensated case by implementation of single SVC to the system. Table 1 shows the voltage magnitudes and angles of the base case after calculating load flow. All busses are within limits except FAR, which is below the limits. Figure 5 shows that most of 110 kV busses are near the lower limits.

Table 1: Voltage profile of the base system

Bus	V[p.u.]	Ang [rad]
AFR	0.9629	-0.551
BNT	0.9511	-0.560
FAR	0.9498	-0.564
FRZ 220	1.0428	-0.324
GAD 220	1.0279	-0.449
GAM 220	1.0100	-0.472
GAM	0.9640	-0.548
GER 220	1.0450	-0.322
IBA 220	1.0192	-0.387
IBA	1.0160	-0.501
IZB	0.9659	-0.643
IZG	0.9793	-0.505
JAS 220	1.0450	-0.471
JAS	1.0129	-0.511
KAB 220	1.0163	-0.215
KAB 500	1.0310	-0.335
KHE	1.0057	-0.543
KHN	1.0400	-0.518

KLX	0.9721	-0.541
KLX 220	1.0128	-0.414
KUK	1.0118	-0.536
LOM	0.9671	-0.546
MAR 500	1.0000	0.000
MHD 220	0.9824	-0.399
MHD	0.9722	-0.497
MRK 500	1.0163	-0.206
MRK 220	0.9934	-0.375
MUG	0.9551	-0.558
OMD	0.9607	-0.516
SHG	0.9619	-0.553

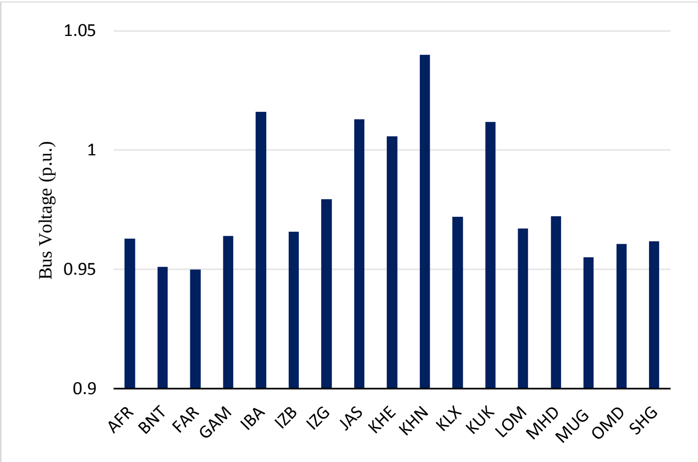

Figure 5: Voltage magnitude of 110 kV busses.

Voltage stability analysis is done for the base case using CPF method, the critical loading point where the Jacobian matrix becomes singular occurs at λ= 1.834879 p.u. and the most critical buses at this point are shown in table 2 below.

Table 2: Critical Buses of base case.

λ = 1.834879	
Bus	Voltage
KLX	0.8377
LOM	0.8239
AFR	0.8168
SHG	0.8053
GAM	0.7944
FAR	0.7876
MUG	0.7744
BNT	0.7614
OMD	0.7385

The weakest bus in the system is OMD with voltage 0.7385 p.u. at the maximum (critical) loading point. Figure 6 shows P-V curve of the weakest three buses MUG, BNT and OMD.

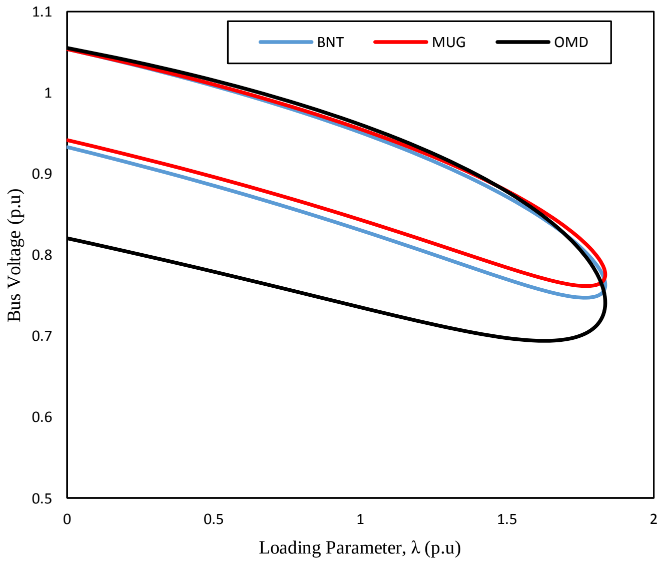

Figure 6: P-V curves of MUG, BNT and OMD.

According to CPF results, SVC is connected at bus OMD. Figure 7 illustrates the impact of SVC on system voltage profile; the injected reactive power of SVC is 78.3 MVAr.

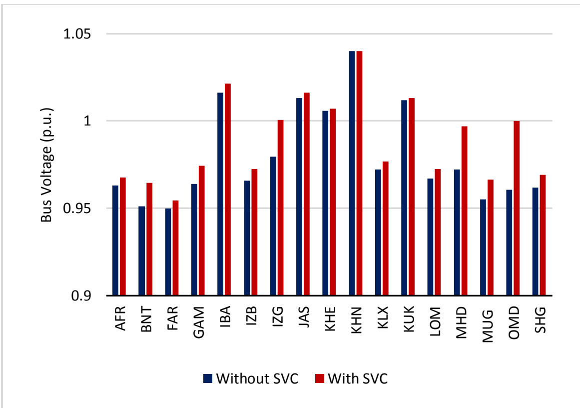

Figure 7: Voltage magnitude of 110 kV buses

Maximum loading point of the compensated case is at λ = 1.856653 which indicates that SVC improves system voltage stability margin, table 3 summarizes the improvement of voltage stability of the critical buses and figure 8 shows the corresponding P-V curves.

Table 3: the improvement of voltage stability of the critical buses

	Base case λ=1.834879	With SVC λ=1.856653
Bus	Voltage (p.u.)	Voltage (p.u.)
MUG	0.7744	0.7814
BNT	0.7614	0.7701
OMD	0.7385	0.7683

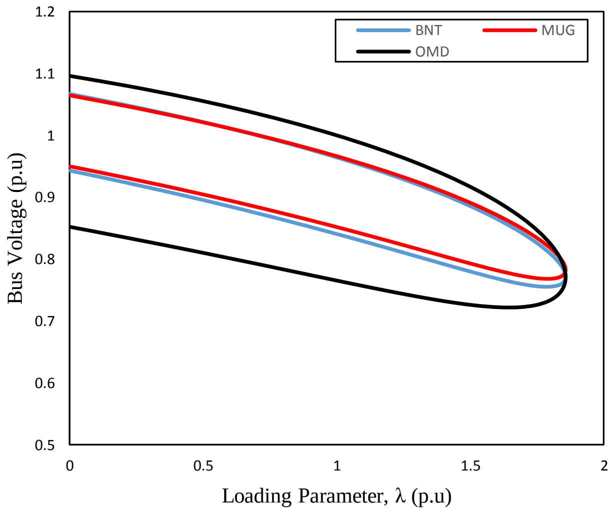

Figure 8: P-V curves of MUG, BNT and OMD with SVC.

SVC at bus OMD improves voltage stability while keeping the voltage magnitude in the acceptable region for all buses. When the maximum limit reached, SVC will be exactly like a fixed shunt capacitor in behavior, so close attention has to be taken for selecting the correct size.

VI. Conclusion

Continuation power flow is described and applied for a part of Sudan national grid to check and investigate the voltage stability status; the study showed that bus OMD is the weakest bus. SVC is introduced and connected to the critical bus in order to improve the system performance and stability. The comparison between results with and without compensation illustrates that SVC enhances voltage stability and it has a great role in increasing stability limits of the system.

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