

# Technique of Optimal Placement of SVC for Voltage Collapse Mitigation

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**Abstract:** Every transmission system has voltage stability limit which may lead to voltage collapse if an undetected bulk transmission network is operated close to its operating limit. This research work uses continuation power flow method to identify voltage collapse point for Bangladesh Power System Network (BPSN). For the identification of weak buses, an analytical based technique of tangent factor has been presented. The risk of voltage collapse has been mitigated by placing SVCs at the weak buses of the system using load flow analysis. Moreover, sensitivity based approach has been introduced to determine optimal location of Static VAR Compensator (SVC) for the voltage security enhancement. A comparative analysis has been documented considering the size of reactive power to improve the loading factor of the overall network at the end of this work.

**Keywords:** Bangladesh Power System Network (BPSN), Static VAR Compensator (SVC), OPF (Optimal Power Flow), Continuation power flow (CPF), Bus Static Participation Factor (BSPF)

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## 1. Introduction

Voltage instability is experienced in a power system when a disturbance causes a progressive uncontrollable decrease in voltage level where voltage instability progress is usually caused by a disturbance or change in operating conditions and increase in electric power demand makes the power system operate close to the limit conditions such as high line current, low voltage level and relatively high power angle differences which indicate the system are operating under heavy loading conditions [1–2].

Voltage collapse is defined as an initial slow progressive but later fast decline in the voltage magnitude of the power system buses which requires inspection of a wide range of system conditions and the steady state analysis can provide much insight into the voltage and reactive power loads problem [1, 2–4]. Numeric techniques have been proposed to take considerable attention for the analysis of this problem [1, 5]. One of them is bifurcation analysis to the load flow equations for a static bifurcation associated with voltage collapse exists at the point load voltages are infinitely sensitive to parameter variations [1, 6]. Another bifurcation technique named

saddle-node-bifurcations associated with multiple load flow solutions undergo as varying reactive power supply parameters [1, 7–8]. The introductory effect of PQ and PV stabilities and control abilities on bus voltage at every load bus is analyzed and the reactive generation at every generator bus to voltage changes at generator buses and reactive load changes at load buses is explained [1, 9–10]. In the continuation of this analysis procedure a tool is proposed in finding the continuation of power flow solution starting from the base load until reaching the steady-state voltage stability limit discussed the physical significance and mathematical equivalence of voltage collapse phenomenon [1, 11–14]. The authors described voltage collapse as a consequence of reactive power imbalance in the system if load increases at any specific bus causes scarcity higher than a reference base case operating point, the system “collapses” with a rapid decline of voltage more than the reserved reactive power can support [1, 15–16].

A few study has been done on voltage collapse constrained loading factor of BPSN considering inadequate reactive power support and poor voltage profile throughout the system network though a preliminary level voltage collapse study is found in [1, 17]. The placement of power electronic based

system such as FACTS to enhance controllability in protecting power system network against voltage collapse [1, 18]. A combined static dynamic procedure of optimal power flow as well as Eigen value analysis using continuation power flow has been explained in [19]. To determine critical bus voltage requirement of Q-support and critical bus angle necessity of P-support based on the largest entry in the left and right Eigen vectors corresponding to zero Eigen value at the collapse point has been proposed in [20]. The critical voltage bus has been considered for SVC placement. Sensitivity has been proposed in reactive power transmission loss to the bus reactive power injection, line reactance and phase shift to determine optimal site for the placement of reactive power supporting equipment [21–22]. Another approach named as voltage phase to identify the most critical bus and line has been suggested for the placement of SVC, TCSC and STATCOM [23]. To enhance dynamic loading margin by SVC installation has been suggested in [24].

To predict the most probable voltage collapse point in EWIS of the BPSN, a continuation power flow based approach is initiated as a brief idea later for the purpose of improving the voltage profile of the overall system. To improve the voltage profile to determine the amount, type and optimal location of additional reactive compensation devices to mitigate the risk of voltage collapse phenomenon in the transmission system, a sensitivity approach has been proposed in this research work.

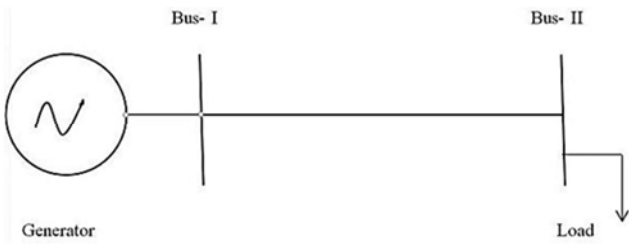


Fig. 1. Two bus representation system [1].

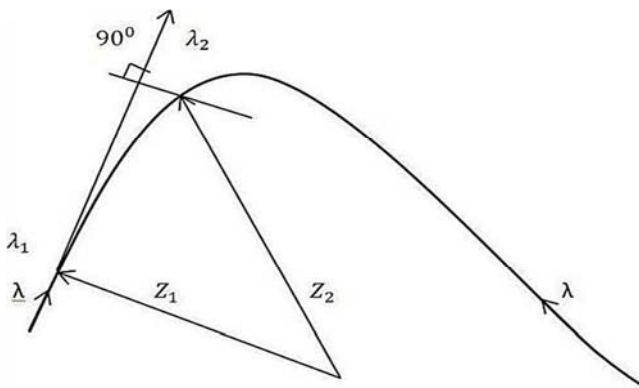


Fig. 2. Technique for continuation power flow [1, 2].

## 2. Methodology

### 2.1. Voltage Collapse

Voltage collapse is the special scenario of voltage instability characterized by low voltage profile and drastic fall of voltage

due to loading and heavy reactive power flow. Continuation power flow techniques are widely acceptable as a valuable identifiable tool for voltage collapse point recognition nose curves determination and estimation of the maximum loading conditions and "critical" solutions of the power system. It consists of the following process:

1. Iterative process,
2. Predictor and
3. Corrective steps.

### 2.2. Analytical Techniques Simulation Tool of Voltage Collapse Identification

#### 1) Bifurcation Technique:

In order to determine voltage collapse point for power system planners and researchers, nonlinear system stability of interest is analyzed using bifurcation technique such as the saddle-node and Hopf bifurcation carried out by changing parameters (Eigenvalue) of the system in load bus power with the presentation of suitable mathematical equation [1].

The presentation of dynamic mathematical formulation behavior of the system is as follows [1, 25–26]:

$$\dot{d} = h(d, e, \lambda, p) \quad (1a)$$

$$o = k(d, e, \lambda, p) \quad (1b)$$

Where,  $d \in R^n$  corresponds the state variables of system, dynamic generators state, loads and other varying time elements in the system, such as SVC controllers, exciter governor of the machine etc. [1–2];

$e \in R^n$  represents to the algebraic variables related to the transmission system and steady-state element models; for example some generating sources and loads in the network [1–2];

$\lambda \in R^m$  represents set of variables that are uncontrollable, continuously varying, typically loading factors which vary with changing system load and leading the system into bifurcation [1–2];

$p \in R^k$  represents for some direct controllable parameter degree of series shunt compensation [1–2];

$h(\cdot)$  and  $k(\cdot)$  stand vector function of algebraic equation and system constrains function respectively [1–2, 17].

Other voltage collapse detection techniques associated with identification of system equilibrium in case of corresponding Jacobians are singular. These equilibrium points referred as point of voltage collapse can mathematically be associated with saddle-node-bifurcation. From equations (1a) and (1b), certain assumptions of equilibrium points can be defined by (2) [1–2, 17].

$$\begin{bmatrix} h(d_0, e_0, \lambda_0 p_0) \\ k(d_0, e_0, \lambda_0 p_0) \end{bmatrix} = F(z_0, \lambda_0 p_0) = 0 \quad (2)$$

Its Jacobian has a zero Eigenvalue [1–2, 23].

SNB points related to voltage collapse determination phenomenon is associated with finding the collapse point  $(h_0, k_0, \lambda_0)$  for a given set of controllable parameters  $p_0$  corresponds to the maximum loading level in p.u. or MW [1–

2].

A two bus system shown in Fig. 1 clarifying SNB for the assumption of base case active and reactive load on bus-II to be  $M_0$  and  $N_0$  respectively increased gradually. Per unit change in real and reactive power loading factor is  $\lambda$  [1]. Therefore,

$$M = M_0(1+\lambda) \quad (3a)$$

$$N = N_0(1+\lambda) \quad (3b)$$

If other unchanged loading parameters in bus-II are increased gradually with a loading factor ( $\lambda$ ), the voltage at bus-II will fall sharply after a certain point known as saddle-node-bifurcation (SNB) or collapse point represents maximum loading point of the system [1, 12].

Among many methods, one particular characteristic of the bifurcation point identification is the Jacobian which becomes singular at that point gradually increasing with the load. Limitations of this trial and error method are that it cannot accurately tell the exact point of bifurcation which occurs beyond the bifurcation point [1].

Another determining method is continuation power flow (CPF) technique consisting of three steps: predictor, corrector and parameterization [1, 2].

Predictor step: It consists of arbitrary steps for  $\lambda$  and state variable from the previously known equilibrium point to predict a new equilibrium point [1, 2].

Corrector step: Its purpose is to find intersection between the perpendicular plane to the tangent vector at the preceding equilibrium and branch reduced step size if the process doesn't converge as the system closes to the solution of power flow equation by varying loading parameter, system Jacobian becomes ill-conditioned shown in Fig. 2 [1, 2].

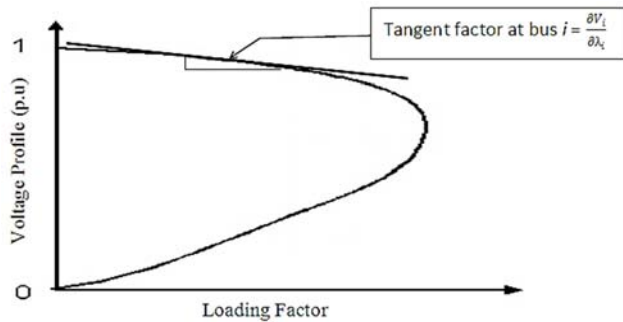


Fig. 3. Tangent factor in P-V curve [31].

Parameterization: It involves non-singular at the saddle-node-bifurcation point which switches loading parameter to the new variables of the system representing highest changes and guarantees the Jacobian of the power flow [1–2, 27].

## 2) Simulation Analysis Tool:

UWPFLOW known as a research tool has been designed to calculate local bifurcations related to system limits or singularities of the system Jacobian used for all continuation based analyses for basic power flow data in WSCC / BPA / EPRI format, IEEE common format and FACTS devices data

in a special exclusive format to this package using Newton-Raphson algorithm for power flow solving equations. Solutions of this tool for static bifurcations can be determined usually by both direct method and continuation methods are provided in ASCII format. Additional advantages of this tool are data with specified options for post processing analyses such as bifurcation diagrams, tangent vectors, left and right eigenvectors at a singular bifurcation point, Jacobians, voltage stability indices etc [1, 17, 28–29].

## 2.3. Proposed Analytical Technique for Weak Bus Identification

The solution of power flow initially is carried out at base case loading condition where the voltage and current at any specific load bus is calculated by gradually increasing load at that bus in each step carrying out the load flow solution observing the voltages and currents at that bus with reference to the load flow solution.

CPF technique is used to detect weak buses of the network where ratio of differential voltage change with respect to the differential load change ratio can be obtained in the process of tracing the bifurcation diagrams [29].

Normally loading factor is dominant in the load related buses. Mathematically, voltage,  $V$  can be expressed as:

$$V_i = F(\lambda_i, Q_i) \quad (4a)$$

$$\text{Tangent Factor (TF), } \frac{\partial V_i}{\partial \lambda_i} = \frac{\partial F(V_i, Q_i)}{\partial \lambda_i} \quad (4b)$$

Where, at bus  $i$ ,  $\lambda_i$  = loading factor,

$Q_i$  = Reactive power,

$V_i$  = Bus voltage.

Tangent factor (shown in Fig. 3) deals the incremental voltage change with loading factor [30].

For the case of weak bus, the voltage will fall drastically for very small change in loading factor. So the change of voltage will be comparatively large with respect to smaller amount of change in loading factor. As a result, the tangent factor will be large.

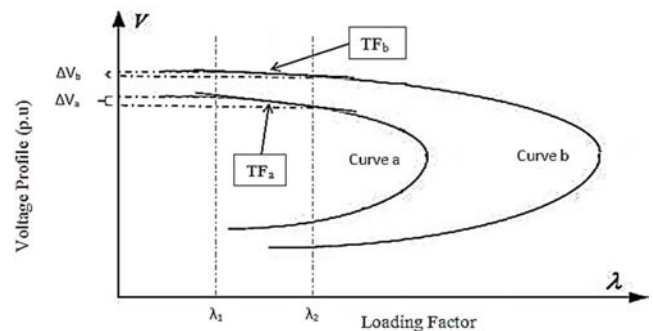


Fig. 4. Weak buses modeling from tangent factor.

From Fig. 4, It has been seen that  $\Delta V_b < \Delta V_a$ . So that  $|TF_a| > |TF_b|$ . It is seen that curve a is weaker bus than curve b with respect to same amount of change in loading factor ( $\lambda_2 - \lambda_1$ ).

#### 2.4. Analytical Technique: Bus Static Participation Factor (BSPF)

The analytical technique termed as bus static participation factor (BSPF) for SVC placement computes sensitivity in system loading factor computed from reactive power balance equation with reference to reactive power generation.

It has already been established that a power system may have saddle-node bifurcation under parameter variations. So considered the static loading margin is the distance between the saddle-node-bifurcation point and the base case operating point. The bus having maximum loading after placement of SVC proves as the candidate bus [31-33]. These participation factors are defined as follows:

$$QD_i = QD_{ib} + \lambda K_{Di} S_{\Delta base} \sin \phi_i \quad (5)$$

Where, at bus i,

$QD_i$  = For base case reactive power demand,

$\lambda$  = Loading factor,

$K_{Di}$  = Constant multiplier indicating the load change,

$$QG_i - (QD_{ib} + \lambda K_{Di} S_{\Delta base} \sin \phi_i) = \sum_{j=1}^n V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) = -V_i^2 B_{ii} + \sum_{j=1, j \neq i}^n V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \quad (8)$$

Partially differentiating (8) with reference to  $QG_i$  defines the sensitivity factor:

$$\frac{\partial \lambda}{\partial QG_i} = \frac{1}{K_{Di} S_{\Delta base} \sin \phi_i} \left[ 1 + 2V_i \frac{\partial V_i}{\partial QG_i} B_{ii} - \sum_{j=1}^n \left\{ \left( V_i \frac{\partial V_j}{\partial QG_i} + V_j \frac{\partial V_i}{\partial QG_i} \right) (Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij})) + V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \left( \frac{\partial \delta_i}{\partial QG_i} - \frac{\partial \delta_j}{\partial QG_i} \right) \right\} \right] \quad (9)$$

The BSPF, given by (9), has been calculated for load buses each in the base case and critical contingency cases at a mentioned point near to the saddle-node-bifurcation point (maximum loadability point).

### 3. Proposed Improved Algorithm of Optimal Placement

For the optimal location of reactive power injection and size determination, the proposed algorithm is implemented in the following steps:

Step 1: The required amount of the SVC is selected by an integer number (bus number) and the SVC position is fixed close to the corresponding bus.

Step 2: It is noticeable that for any reactive power deficiency of any generator bus, the root cause is the associated load bus. So for the purpose of SVC placement, the position is changed to the next load bus.

In the determination of optimal placement a set of weak buses are considered and then calculate the BSPF analysis. Based on the sensitivity analysis, SVCs are placed to the corresponding most sensitive appropriate location.

The proposed algorithm of modeling of SVC optimization is shown in Fig. 5.

In Fig. 5 the iteration will continue on the weak buses. This approach not only considers the sensitivity of buses but also decides the improvement of overall system LF after SVC placement.

$\phi_i$  = Power factor angle of load increase,

$S_{\Delta base}$  = For equivalent MVA load increase, MVA base value is used for scaling.

The injection of reactive power  $Q_i$  at bus-i is:

$$Q_i = QG_i - QD_i \quad (6)$$

Where,  $QG_i$  = Generation of reactive power.

Reactive power  $QT_i$  transmitted at bus-i:

$$QT_i = \sum_{j=1}^n V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \quad (7)$$

Where,  $V_i \angle \delta_i$  = at bus-i complex voltage,

$V_j \angle \delta_j$  = at bus-j complex voltage,

$Y_{ij} \angle \theta_{ij}$  = admittance matrix for  $ij^{th}$  element of the bus,

$n$  = number of total buses in the system.

From (5), (6) and (7), injected reactive power balance equation at the bus-i:

The sensitivity factor,  $\frac{\partial \lambda}{\partial QG_i}$  is connected to load factor with reactive power generation, is the BSPF.

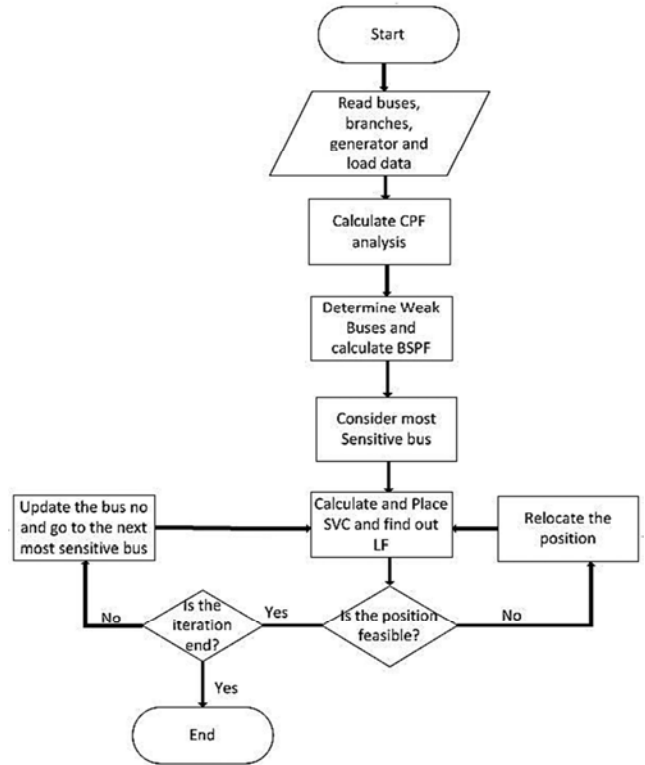


Fig. 5. Algorithm for the proposed technique of SVC optimization.

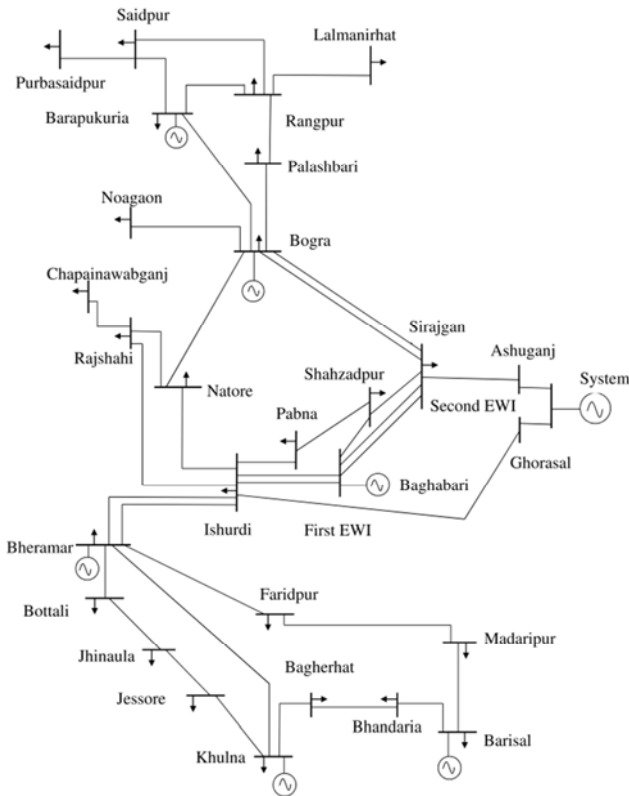


Fig. 6. EWIS of BPSN [1-2].

## 4. Network Modeling

Generated high power in the eastern grid of BPSN is

transmitted to the western grid by means of two tie lines: Ghorasal to Ishurdi (1st EWI) and Ashuganj to Sirajganj (2nd EWI) [1-2].

Fig. 6 shows topology derived from the actual network condition of EWIS in BPSN [1]. Other components of numeric data are shown in Table-1.

Table 1. EWIS Network System Components [17].

Component	Number
Buses	44
Generator	7
Shunts	25
Lines	42
Transformers	14
Load Aggregations	26

## 5. Case Study with Result Analysis

### CPF Analysis:

PV curve calculated by bifurcation analysis indicates the overall network voltage collapse identification without SVC compensation close to SNB for increasing LF [1].

In CPF analysis the base case voltage collapse phenomenon is observed at LF 0.98 shown in Fig. 7.

From Fig. 3, it shows that if the loading factor increases considering others in steady state and unchanged, voltage profile decreases with load. At SNB point is defined the minimum point where loading causes incremental decrease if voltage profile. After SNB with increasing load voltage profile will drastically fall. Without SVC compensation, overall network SNB is found as 0.98.

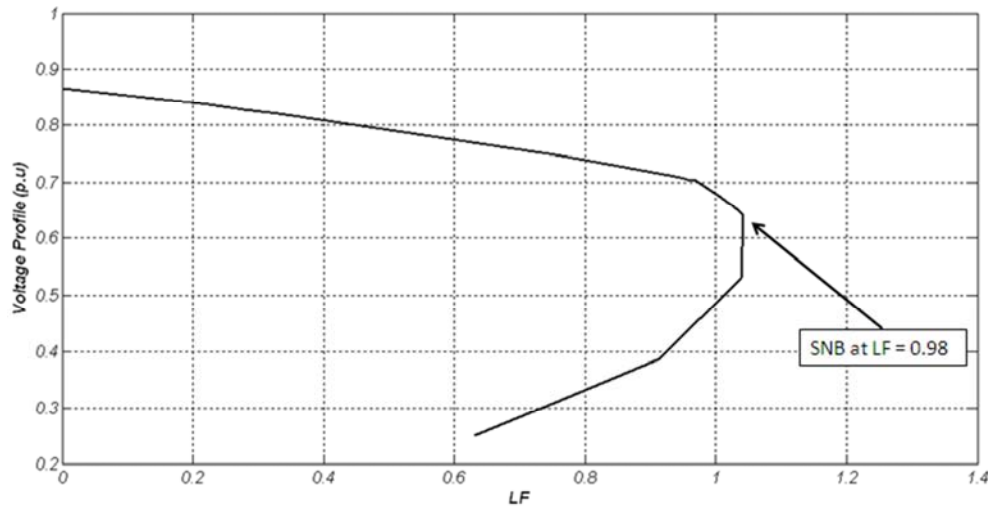


Fig. 7. Bifurcation diagram of EWIS.

Table 2. CPF Analysis of the Overall EWIS with SNB Point.

Corresponding More Affected Buses	Corresponding Less Affected Buses	SNB Point
Bhandaria bus, Madaripur bus, Barisal bus, Madaripur bus, Faridpur bus, Barisal bus, Purbasaidpur bus, Saidpur bus.	Bagherhat bus, Bheramara Region bus, Rangpur bus, Barapukuria Region bus, Rajshahi bus.	0.98

From the above data it is clear that, the correspondence near zones of the affected buses in the power system has significant voltage violability. So by increasing the LF of the load buses,

the voltage profile of those buses is gradually decreasing. So, load buses along with the corresponding near buses face the collapse phenomenon.



Due to increase of LF the associated buses: Barisal, Bhandaria, Faridpur and Madaripur experience collapse phenomenon except bus Bagherhat and bus Bheramara region. The reason is behind this for bus Bagherhat one side of it is connected to collapse buses and the other side is associated with generator bus (see Fig. 6). From the generator bus Khulna Region; it has got the necessary amount of reactive power support. That is why the voltage collapse phenomenon is not as severe as the other buses. Similarly, it can be explained for Bheramara Region. In this case the generator bus is also that bus (see Fig. 6).

Due to increase LF of the buses: Saidpur and Purbasaidpur, the associated buses experience collapse phenomenon except bus Rangpur and bus Barapukuria Region. The cause behind for this is that one side of bus Rangpur is attached to collapse bus and the other side is to bus generator (see Fig. 6). From the generator bus Barapukuria Region; it has got the necessary amount of VAr support. That is the reason of voltage collapse phenomenon is not as severe as the other buses. Similarly, it can be explained for bus Purbasaidpur. In this case the generator bus is in Barapukuria Region (see Fig. 6).

Due to increase LF of the bus Chapainawabganj, the associated bus Rajshahi does not have the severe collapse phenomenon. The reason behind this for Chapainawabganj bus which one side of it is connected to load and the other side is closely involved to a generator bus (see Fig. 6). From the generator bus Bogra Region; it has got the necessary amount of reactive power support. That is why the voltage collapse phenomenon is not as severe as the other buses.

By increasing the LF of affected buses, the voltage profile of those buses is gradually decreasing. The increase in LF also effect of those near buses. As a result of which, the overall system is facing voltage collapse phenomenon.

#### Weak Buses Identification:

Continuation power flow (CPF) analysis is performed on the base case of EWIS set-up in BPSN to monitor the tangent factor at maximum point of loading to identify several weak points presented in Table-3 [17].

**Table 3.** Tangent Factors Analysis of Weak Buses in EWIS of BPSN.

Bus Name	Analysis of [Tangent Factor (TF)]
Purbasaidpur bus	0.15078
Madaripur bus	0.141487
Barisal bus	0.13475
Faridpur bus	0.12567
Saidpur bus	0.116977
Chapainawabganj bus	0.10801
Bhandaria bus	0.0834

The performed analysis of CPF in overall is summarized in Table-2.

#### Required Reactive Power Support Calculated by Load Flow Analysis:

To improve the voltage profile from voltage collapse phenomenon load flow analysis has been done using CPF analysis to identify the required amount of reactive power needed to improve the network. In this analysis, reactive power injection has been done by SVC placement. In Table-4, required amount of reactive power and the improvement of loading factor after placement of SVC are presented.

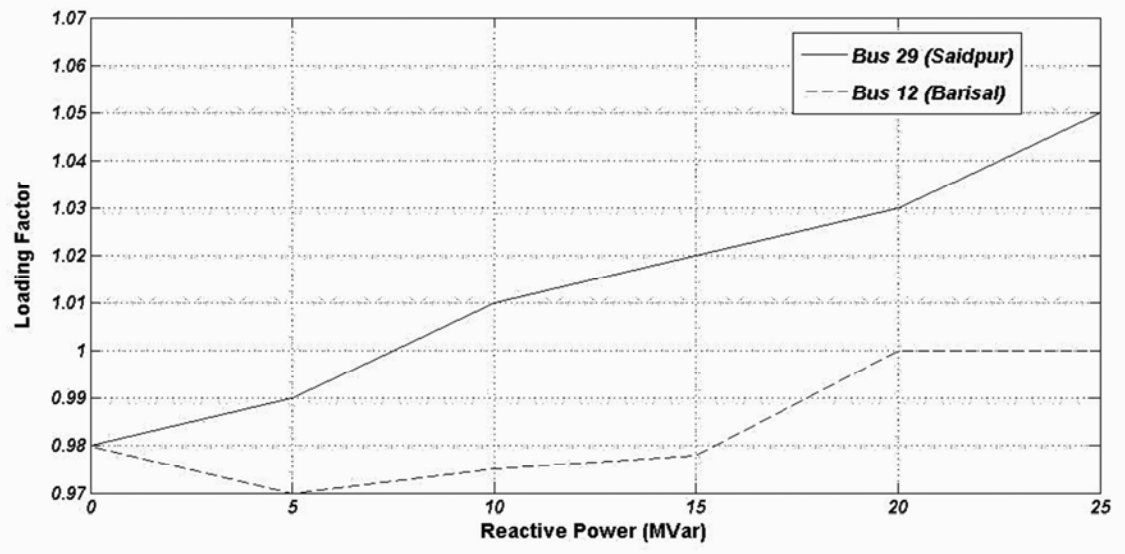
**Table 4.** Requirement of Reactive Power and Improvement of Loading Factor.

Total Reactive Power (MVar) from Load Flow Analysis	Improved Loading Factor (LF) After SVC Placement
74.77	1.04

#### BSPF Analysis:

The proposed analytical technique of BSPF computed for the placement of reactive power for the base cases using (9) at a loading value in PV curve of SNBP are given in Table-5.

The static loading margins were computed for the base case and under static voltage stability cases, without SVC in the system, and with SVC placed at buses using the UWPFLOW. It is observed from Table-5 that the Saidpur bus has maximum of BSPF for the base case. So the placement of SVC at bus Saidpur causes maximum enhancement in static loading margin.



**Fig. 8.** Comparison of reactive power effect between bus Saidpur and bus Barisal.

**Table 5.** BSPF Values for the Most Sensitive Buses (BPSN).

Bus Name	Bus Static Participation Factor (BSPF)
Saidpur bus	0.0506
Purbasaidpur bus	0.0274
Chapainawabganj bus	$5.862 \times 10^{-3}$
Faridpur bus	$3.253 \times 10^{-3}$
Madaripur bus	$1.885 \times 10^{-3}$
Bhandaria bus	$1.1516 \times 10^{-3}$
Barisal bus	$1.1319 \times 10^{-3}$

**Table 6.** Analysis of VAR Injection in the Sensitive Buses.

Bus Name	Improvement of system LF by applying reactive power					
	Base case	5 MVar	10 MVar	15 MVar	20 MVar	25 MVar
Saidpur bus	0.98	0.99	1.01	1.02	1.03	1.05
Purbasaidpur bus	0.98	0.99	1.01	1.02	1.03	1.05
Chapainawabganj bus	0.98	0.978	0.982	0.987	0.99302	1.00
Faridpur bus	0.98	0.974	0.9778	0.982	1.00	1.00
Madaripur bus	0.98	0.973	0.976	0.98	1.00	1.00
Bhandaria bus	0.98	0.97	0.974	0.998	1.00	1.00
Barisal bus	0.98	0.97	0.975	0.978	1.00	1.00

### Analysis of Optimal Placement:

To understand the effect of the placement of SVC in the sensitive bus, consider two buses (i.e. bus Saidpur and bus Barisal) in the sensitivity list. According to the sensitivity list based on BSPF and proposed algorithm, bus Saidpur is the most sensitive bus and bus Barisal is less sensitive bus. Since bus Saidpur is the most sensitive bus, the placement of SVC of that bus will be important. So it will affect much to enhance the overall system loading factor. Although bus Barisal is comparatively less sensitive bus, it will also affect the overall system loading factor. The contribution of the placement of SVC of that bus has less effect in the overall system loading factor. The comparison of SVC effect of those buses in the overall system loading factor is shown in Fig. 8.

From Figure 8, it has been seen that bus Saidpur is more sensitive than bus Barisal. So according to the proposed method it is observed in simulation that with the increase of reactive power in bus Saidpur, the overall system loading factor has been increased. Another important thing bus Barisal is less stable than bus Saidpur. That's why after injecting 5MVar reactive power, bus Barisal LF is decreased instead of increasing. Later with increasing of reactive power its LF increases.

Comparison between Standard Load Flow Analysis and Improved Proposed Algorithm of Optimal Placement:

In the discussed algorithm of optimal placement of reactive power support such as SVC, the suitable location has been identified. So by injecting the least required amount of SVC in comparison to standard analysis, desired amount of improvement is achieved.

The comparison between load flow analysis and the sensitivity algorithm method is shown in Table-7.

From Table -6, it has been seen that the placement of SVC in the sensitive buses contribute the overall system loading factor significantly. Here, the bus Saidpur and bus Purbasaidpur are the very closest buses (see Fig. 6). So the placement of SVC of those buses makes the same effect of the overall system loading factor. Meanwhile, bus Faridpur, bus Madaripur, bus Bhandaria and bus Barisal are the nearest buses. So the placement of SVC of those buses gets the similar type result.

**Table 7.** Comparison between load flow analysis and the sensitivity based algorithm.

Process	Reactive power (MVar) Requirement	LF
Load Flow	74.77	1.04
Proposed Technique	25	1.05

From Table-7, it has been seen that by supplying less reactive power support in the most sensitive bus, the overall network loading factor can be increased significantly in comparison to load flow analysis.

## 6. Conclusions

The application of SVC at weak buses has been done for the improvement of voltage profile having probability to voltage collapse. The loading capability of the buses has been improved dramatically by the application of SVCs. The tests have been performed on the EWIS (East West Interconnected System) of BPS network. The test method has been verified by a test system of two buses. Prediction of voltage collapse using CPF analysis for determining the weak buses of the system has been done by SNB analysis locating the position of the collapse point. The weak bus has been presented by the PV diagram. It has also been helpful in determining the VAR requirements in weak buses. Improvement after installing SVCs has also been presented via the PV diagram of the weak buses. The size of the VAR compensation has been calculated by the steady state analysis. Generator with desired voltage level and zero real power has been added to the weak buses and their reactive power outputs have been measured to get an estimate of the VAR injection required at the weak buses. The priority order has been made on the basis of BSPF. Weak

buses with higher value of BSPF have been given priority in placing SVCs. System stability has been tested by the steady state analysis on EWIS. Methods for finding the weakest buses have been developed. Corrective measures have been taken to minimize the amount of total VAR compensation. The placement of the SVC devices has been optimized to reduce installation cost and improve steady state performance of the overall system.

Only SVCs have been considered as reactive power sources in this work. Other FACTS devices like STATCOMs would be more suitable for the similar application. Time domain analysis could be included for ensuring transient stability. In addition to that contingency analysis can be performed to ensure system security.

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