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Optimum Load Shedding in Power System Strategies with Voltage Stability Indicators

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Abstract

An optimal load shedding strategy for power systems with optimum location and quantity of load to be shed is presented in this paper. The problem of load shedding for avoiding the existence of voltage instability in power systems is taken as a remedial action during emergency state in transmission and distribution sector.Optimum location of loads to be shed is found together with their optimum required quantity. L-Indicator index is in used for this purpose with a modified new technique. Applications to be standard 6 bus Ward-Hale test system and IEEE – 14 bus system are presented to validate the applicability of the proposed technique to any system of any size.

1. Introduction

The major objective of power systems is to supply electricity to its customers. During emergency state of the power system, it may shed partial loads to ensure the power supply to important loads, as the last resort to maintain system integrity. Load shedding in bulk power system has been studied many years [1–6].

In electric power systems heavy loading may lead to voltage instabilities or collapses or in the extreme to complete blackouts. One technique of avoiding voltage instability is to shed some consumer's loads in Order to draw the operating point for away from the critical voltage value.

Many techniques have been developed [7–13] to minimize the load curtailment without violating the system security constraints. The emergency state in the power System with distributed generations has been formulated the load shedding is solved as an optimization problem [14]. Ying Lu *et al.* [15] has proposed a load shedding scheme, working with various load models, such as single-motor model, two-motor model, and composite model. Armanda *et al.* [16] have adopted a Distributed Interruptible Load Shedding (DILS) program instead of the traditional methodologies based on the separation of some users and/or entire distribution feeders, according to programmed plans of emergency. Andrzej Wiszniewski [17] have formulated a new method for estimating

the voltage stability margin, which utilizes local measurements and applied criterion is based on the very definition of the voltage stability. Zhiping Ding *et al.* [18] have developed an expert-system-based load shedding scheme (LSS) for ship power systems. Emmanuel J. Thalassinakis *et al.* [19] have built an efficient computational methodology that can be used for calculating the appropriate strategy for load shedding protection in autonomous power systems.

In this paper a fast method for determining the location and quantity of the load to be shed in order to avoid risk of voltage instability is presented. The method defines clearly the bus where load shedding should make. A relation between voltage stability indicator changes and load power to be shed is developed. Using the relation the amount of load to be shed is determined. An algorithm has been developed for determining the location and quality of load to be shed and tested with tbe standard 6 buses Ward-Hale test system and IEEE – 14 bus system. The proposed method is valid for any system of any size at any loading conditions.

2. Mathematical Calculation for Load Shedding Using Voltage Stability Indicator- METHOD I

From the indicator proposed in [3] voltage stability indi-

cator at bus j can determine by

$$B_j = \left| 1 - \frac{\sum\limits_{i \in \alpha G} C_{ji} V_i}{V_j} \right| \qquad j \in \alpha L \qquad (1)$$

where

α_L : Set of load buses.

α_G : Set of generator buses.

V_i : Voltage of generator bus i.

V_j : Voltage of load bus j.

C_{ji} : Elements of matrix C determined by

$$[C] = -\left[B_{LL} \right]^{-1} \left[B_{LG} \right] \qquad (2)$$

$\left[B_{LL} \right]^{-1}$ is the imaginary part of the matrix $\left[Y_{LL} \right]^{-1}$

$\left[B_{LG} \right]$ is the imaginary part of the matrix $\left[Y_{LG} \right]$

$\left[B_{LL} \right]^{-1}$ and $\left[B_{LG} \right]$ are susceptance matrices.

$\left[Y_{LL} \right]$ and $\left[Y_{LG} \right]$ are submatrices for the Y-Bus matrix.

The indicator at bus j, determined by equation (1) can be separated into real and imaginary parts $\left(B_j^R, B_j^I \right)$:

$$B_j = 1 - \frac{\sum\limits_{i=1}^{\alpha G} C_{ji} |V_i| \underline{\delta i}}{|V_j| \underline{\delta j}} \qquad (3)$$

$$B_j^R + j B_j^I = 1 - \frac{\sum\limits_{i=1}^{\alpha G} C_{ji} |V_i| \underline{\delta i - \delta j}}{|V_j|} \qquad (4)$$

$$B_j^R = 1 - \frac{\sum\limits_{i=1}^{\alpha G} C_{ji} |V_i| \cos(\delta i - \delta j)}{|V_j|} \qquad (5)$$

$$B_j^I = -\frac{\sum\limits_{i=1}^{\alpha G} C_{ji} |V_i| \sin(\delta i - \delta j)}{|V_j|} \qquad (6)$$

δi, δj : voltage angles at buses i and j

$|V_i|$, $|V_j|$: voltage magnitudes at buses i and j

The voltage stability indicator at each bus is a function of voltage angle and magnitude. The real imaginary part of indicator can be expressed as:

$$\begin{aligned} B^I &= F_1 \left(\delta, |V| \right) \\ B^R &= F_2 \left(\delta, |V| \right) \end{aligned} \qquad (7)$$

The partial derivative of Equations (5) and (6) with respect to voltage angle and magnitude changes can be determined as:

$$\begin{bmatrix} \Delta B^I \\ \Delta B^R \end{bmatrix} = \begin{bmatrix} \dfrac{\partial B^I}{\partial \delta} & \dfrac{\partial B^I}{\partial |V|} \\[2mm] \dfrac{\partial B^R}{\partial \delta} & \dfrac{\partial B^R}{\partial |V|} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} = [T] \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \qquad (8)$$

Matrix [T] is sensitivity matrix between indicator changes and voltage angle and magnitude changes
Coefficient of matrix [T] can be determined as

$$\frac{\partial B_J^I}{\partial \delta i} = -\frac{C_{ji} |V_i| \cos(\delta i - \delta j)}{|V_j|} \qquad i \in \alpha_{G,} i \neq s \qquad (9)$$

(S indicates the swing bus)

$$\frac{\partial B_j^I}{\partial \delta j} = \frac{\sum\limits_{i \in \alpha G} C_{ji} |V_i| \cos(\delta i - \delta j)}{|V_j|} = -\left(B_j^R - 1 \right) f \qquad (10)$$

$$\frac{\partial B_j^R}{\partial \delta i} = \frac{C_{ji} |V_i| \sin(\delta i - \delta j)}{|V_j|} \qquad (11)$$

$$\frac{\partial B_j^R}{\partial \delta j} = -\frac{\sum\limits_{i \in \alpha G} C_{ji} |V_i| \sin(\delta i - \delta j)}{|V_j|} = B_j^I \qquad (12)$$

$$\frac{\partial B_j^I}{\partial |V_j|} = \frac{\sum\limits_{i \in \alpha G} C_{ji} |V_i| \sin(\delta i - \delta j)}{|V_j|^2} = -\frac{B_j^I}{|V_j|} \qquad (13)$$

$$\frac{\partial B_j^R}{\partial |V_j|} = \frac{\sum\limits_{i \in \alpha G} C_{ji} |V_i| \cos(\delta i - \delta j)}{|V_j|^2} = -\frac{B_j^R - 1}{|V_j|} \qquad (14)$$

From conventional Newton-Raphson load flow we obtain a linear relation between changes in voltage phases/magnitudes and active/reactive power injections as:

$$\begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} = [j]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \qquad (15)$$

Sub (15) in (8) we get a relationship between real and imaginary part indicators and injected power as:

$$\begin{bmatrix} \Delta B^I \\ \Delta B^R \end{bmatrix} = [T][j]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \qquad (16)$$

A relationship between changes in indicators at load bus j and power injections at all load buses can be obtained:

$$\Delta B_j^I = S_{11} \Delta P_j + S_{12} \Delta Q_j \qquad (17)$$

$$\Delta B_j^R = S_{21} \Delta P_j + S_{22} \Delta Q_j \qquad (18)$$

The active and reactive loads are not independent; one cannot shed active load, without curtailing reactive loads. Usually, a relation between active and reactive load at bus j can be obtained as follows. Here the load power factor is assumed to be constant at each load bus.

$$Pf_j = \frac{Q_j}{P_j} \qquad j \in \alpha_L$$

$$Pf_j = \frac{\Delta Q_j}{\Delta P_j}$$

$$\Delta Q_j = Pf_j \Delta P_j \qquad (19)$$

Sub (19) in (17and18) we get a relationship between changes of the indicator at bus j and changes in active power injected at the same bus can be obtained as

$$\Delta B_j^I = S_{11} \Delta P_j + S_{12} Pf_j \Delta P_j \qquad (20)$$

$$\Delta B_j^R = S_{21} \Delta P_j + S_{22} Pf_j \Delta P_j \qquad (21)$$

$$\Delta B_j^I = S_1 \Delta P_j \qquad (22)$$

$$\Delta B_j^R = S_2 \Delta P_j \qquad (23)$$

where

$$S_1 = S_{11} + S_{12} Pf_j$$

$$S_2 = S_{21} + S_{22} Pf_j$$

We know

$$\Delta B_j = \sqrt{(\Delta B_j^I)^2 + \left(\Delta B_j^R\right)^2} \qquad (24)$$

$$\Delta B_j = \sqrt{S_1^2 \Delta P_j^2 + S_2^2 \Delta P_j^2} \qquad (25)$$

$$\Delta B_j = \sqrt{(S_1^2 + S_2^2)\Delta P_j^2}\, s$$

$$\Delta B_j = \Delta P_j \sqrt{(S_1^2 + S_2^2)} \qquad (26)$$

$$\Delta P_j = \frac{\Delta B_j}{\sqrt{(S_1^2 + S_2^2)}} \qquad (27)$$

$$\Delta Q_j = Pf_j \Delta P_j \qquad (28)$$

Using Equation (28) reactive power to be shed at bus j can be obtained if the active power to be shed at bus j is known.

3. Improved Method for Load Shedding By Voltage Stability Indicator

There are several methods for improving the voltage conditions in a power system as suggested in various articles.

In the improved method, the voltage profile is enhanced by determining the location and quantity of load to be shed, such that voltage instability can be avoided.

This method is based on the indicators of risk of voltage instability suggested by P. Kessel and H. Glavitsch [3]. The improved technique is a modification of the technique for previous section. It defines clearly the bus where the load shedding should be made. A relation between indicator changes and load powers to be shed is developed here. Using this relation, the amount of load to be shed is determined, for any operational situation.

4. Mathematical Calculation for Load Shedding Using Improved Voltage Stability Indicator- METHOD II

Kessel and Glavitsch [3] have developed a voltage stability indicator at load bus j

$$L_j = \left| 1 - \frac{\sum_{i \in \alpha G} F_{ji} V_i}{V_j} \right| \qquad J \in \alpha L \qquad (29)$$

where

α_L : Set of load buses.

α_G : Set of generator buses.

V_i : Voltage of generator bus i.

V_j : Voltage of load bus j.

$$[Y] = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \qquad (30)$$

$$[F] = -[Y_{LL}]^{-1}[Y_{LG}] \qquad (31)$$

$Y_{GG}, Y_{LL}, Y_{LG}, Y_{GL}$: Elements of system admittance matrix

A global voltage stability indicator of a power system is given by L, $0 \le L \le 1$

0: far away from voltage instability point.

1: at voltage instability point.

The indicator at bus j determined by Equation (29) can be separated into real and imaginary part (L_j^R, L_j^I)

$$L_j^R + jL_j^I = 1 - \frac{\sum_{i \in \alpha G} |F_{ji}| |V_i| \angle \theta_{ji} + \delta_i - \delta_j}{|V_j|} \qquad (32)$$

$$L_j^R = 1 - \frac{\sum_{i \in \alpha G} |F_{ji}| |V_i| \cos \angle \theta_{ji} + \delta_i - \delta_j}{|V_j|} \qquad (33)$$

$$L_j^I = -\frac{\sum_{i \in \alpha G} |F_{ji}||V_i| \sin|\theta_{ji} + \delta_i - \delta_j}{|V_j|} \quad (34)$$

The voltage stability indicator at each bus is a function of voltage angles and magnitudes. The real and imaginary parts of indicators can be expressed as:

$$L^I = F_1 d\left(\delta, |V|\right) \quad (35)$$

$$L^R = F_2\left(\delta, |V|\right) \quad (36)$$

The partial derivative of Equations (33) & (34) with respect to voltage angle and magnitude changes can be determined as

$$\begin{bmatrix} \Delta L^I \\ \Delta L^R \end{bmatrix} = \begin{bmatrix} \dfrac{\partial L^I}{\partial \delta} & \dfrac{\partial L^I}{\partial |V|} \\ \dfrac{\partial L^R}{\partial \delta} & \dfrac{\partial L^R}{\partial |V|} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} = [T] \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (37)$$

Matrix [T] is the sensitivity matrix between indicator changes and voltage angle and magnitude changes
Coefficient of matrix [T] can be determined as

$$\frac{\partial L_J^I}{\partial \delta i} = -\frac{|F_{ji}||V_i| \cos\left(\theta_{ji} + \delta_i - \delta_j\right)}{|V_j|} \quad i \in \alpha G, i \neq s \quad (38)$$

(S indicates the swing bus)

$$\frac{\partial L_j^I}{\partial \delta j} = \frac{\sum_{i \in \alpha G} |F_{ji}||V_i| \cos\left(\theta_{ji} + \delta_i - \delta_j\right)}{|V_j|} = (L_j^R - 1) \quad (39)$$

$$\frac{\partial L_j^R}{\partial \delta_i} = \frac{|F_{ji}||V_i| \sin\left(\theta_{ji} + \delta_i - \delta_j\right)}{|V_j|} \quad (40)$$

$$\frac{\partial L_j^R}{\partial \delta_i} = -\frac{\sum_{i \in \alpha G} |F_{ji}||V_i| \sin\left(\theta_{ji} + \delta_i - \delta_j\right)}{|V_j|} = L_j^I \quad (41)$$

$$\frac{\partial L_j^I}{\partial |V_j|} = \frac{\sum_{i \in \alpha G} |F_{ji}||V_i| \sin\left(\theta_{ji} + \delta_i - \delta_j\right)}{|V_j|^2} = \frac{L_j^I}{|V_j|} \quad (42)$$

$$\frac{\partial L_j^R}{\partial |V_j|} = -\frac{\sum_{i \in \alpha G} |F_{ji}||V_i| \cos\left(\theta_{ji} + \delta_i - \delta_j\right)}{|V_j|^2} = \frac{L_j^R - 1}{|V_j|} \quad (43)$$

Form conventional Newton-Raphson Load flow we obtain a linear relation between changes in voltage phase/magnitudes and active/reactive power injections

as:

$$\begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} = [j]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (44)$$

Sub (44) in (37) we get a relationship between real and imaginary parts of indicators and injected power as:

$$\begin{bmatrix} \Delta L^I \\ \Delta L^R \end{bmatrix} = [T][j]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (45)$$

A relationship between changes in indicators at load bus j and power injections at all load buses can be obtained:

$$\Delta L_j^I = S_{11} \Delta P_j + S_{12} \Delta Q_j. \quad (46)$$

$$\Delta L_j^R = S_{21} \Delta P_j + S_{22} \Delta Q_j \quad (47)$$

The active and reactive loads are not independent: one cannot shed active loads without reducing reactive loads. Usually a relation between active and reactive load can be obtained as follows. Here the load power factor is assumed to be constant at each load bus.

$$Pf_j = \frac{Q_j}{P_j} \quad j \in \alpha_L$$

$$Pf_j = \frac{\Delta Q_j}{\Delta P_j}$$

$$\Delta Q_j = Pf_j \Delta P_j \quad (48)$$

Sub (48) in (46 and 47) we get a relationship between changes of the indicator at bus j and changes in active power injected at the same bus can be obtained as

$$\Delta L_j^I = S_{11} \Delta P_j + S_{12} Pf_j \Delta P_j \quad (49)$$

$$\Delta L_j^R = S_{21} \Delta P_j + S_{22} Pf_j \Delta P_j \quad (50)$$

$$\Delta L_j^I = S_1 \Delta P_j \quad (51)$$

$$\Delta L_j^R = S_2 \Delta P_j \quad (52)$$

where

$$S_1 = S_{11} + S_{12} Pf_j$$

$$S_2 = S_{21} + S_{22} Pf_j$$

$$\Delta L_j = \sqrt{(\Delta L_j^I)^2 + \left(\Delta L_j^R\right)^2} \quad (53)$$

$$\Delta L_j = \sqrt{S_1^2 \Delta P_j^2 + S_2^2 \Delta P_j^2} \quad (54)$$

$$\Delta L_j = \sqrt{(S_1^2 + S_2^2)\Delta P_j^2}$$

$$\Delta L_j = \Delta P_j \sqrt{(S_1^2 + S_2^2)} \quad (55)$$

$$\Delta P_j = \frac{\Delta L_j}{\sqrt{(S_1^2 + S_2^2)}} \qquad (56)$$

$$\Delta Q_j = Pf_j \Delta P_j \qquad (57)$$

Using Equation (57) reactive power to be shed at bus j can be obtained if the active power to be shed at bus j is know.

5. Algorithm for Calculation Load to Be Shed

The step by step procedure of load shedding algorithm is given as follows

Step 1
Carry out load flow by Newton Raphson Method.
Step 2
Calculate voltage stability indicator for all load buses and find Lmax.
Step 3
Check Lmax $\geq$ Lcritical, if exceeds we have to shed a part of load at that bus with
maximum value of L, goto next step. Else there is no need to shed the load stop.
Step 4
Using Equations (56 and 57), calculate the required load to be shed.
Step 5
Remove this load and goto step (1)

i.e. (subtract this ΔP_j and ΔQ_j from the jth load bus).

6. Numerical Examples, Simulation Results and Analysis

The study has been conducted on test cases with standard 6 bus Ward-Hale test system and IEEE-14 bus test system. The voltage stability indicator for all load buses are computed by two methods for various load patterns and results are tabulated.

To verify the feasibility of the improved method, two different power systems were tested, under various base cases. The solutions were compared by their solution quality and computation efficiency. From the experiences of many experiments the optimum load shedding algorithms have been used to solve the above test cases and are results are tabulated. For implementing the above algorithm, the simulation studies were carried out on P-IV, 2.4 GHz, 512 MBDDR RAM systems in MATLAB environment. The load shedding results for the first test case with the corresponding base cases are tabulated in Tables 1-6.

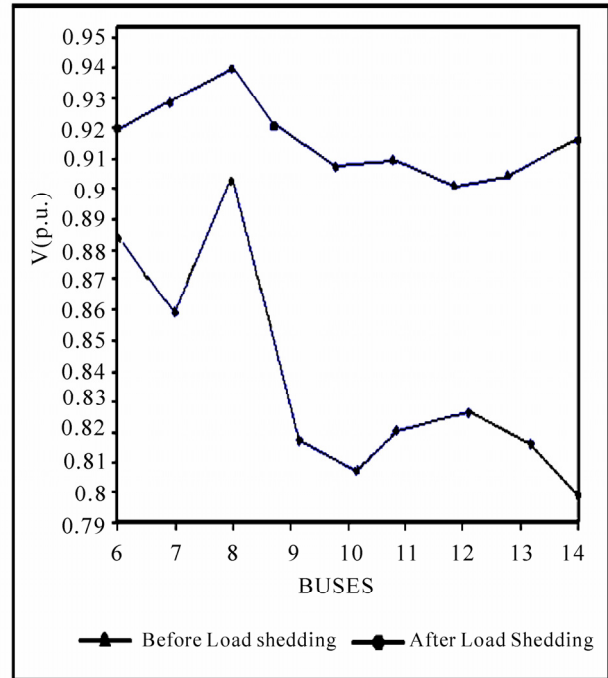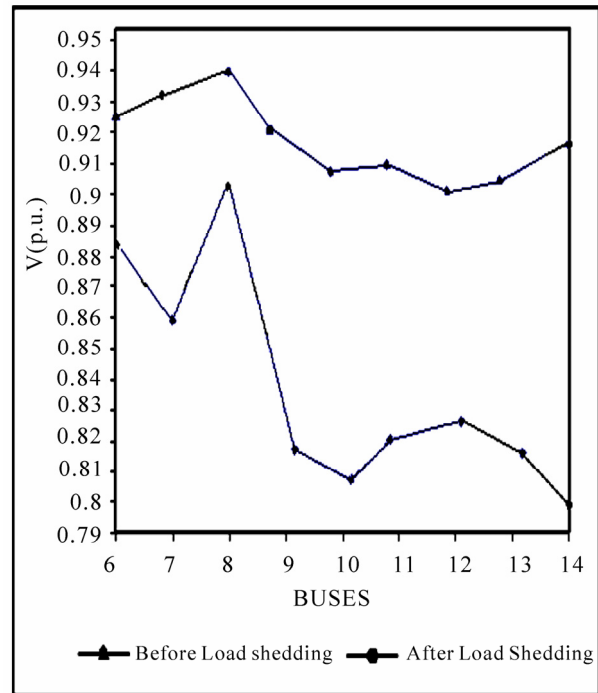**Figure 1. Voltage profile for standard 6 bus ward-hale test system.**

Figure 2. Voltage profile for IEEE-14 bus test system.

Table 1 illustrates the results of load flow solution of 1.5 times the base power; the maximum value of the B indicator is 0.572051 at bus 5. Therefore it is the bus at which load must be shed. Using the proposed method,

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the quantity of load to be shed is found and shown in the same table. The B indicator after shedding and the bus voltage magnitude after each load shed is given in the same Table 1.

In case study I using method 1 the maximum value of indicators occur at bus 3, 5 and 6. Using the improved method the impact of maximum value of indicators occurred at bus 3, 5 and 6 got reduced and illustrated in Table 2.

The successive load shedding and improvement in voltage magnitude with the maximum value of B indicator less than the B critical value for load flow solution 1.1 times and 1.0 times the base power is illustrated for both the methods were illustrated in Tables 3,4,5 and 6 for 6 bus Ward-Hale test system.

The results from the improved method is compared with the method proposed by T. Quoc Taun *et al.* [4–5] in Tables 7,8,9,10,11,and 12 for IEEE-14 bus system for different loading conditions respectively. Analysis of these tables shows that shedding of selected loads at selected buses improves the voltage magnitude at all buses. In addition, the stability of the system is improved.

The computation time of these two methods for different loading conditions are tabulated in Tables 13 and 14. From these tables, it is very clear that the computation time of the proposed method is slightly higher than method-I .The various results obtained by the two methods show that both the methods are quite effective. But, in the proposed method both resistance and reactance are taken into account hence this method is more accurate and yields more computation time. Figure 1 and Figure 2 show the improved voltage profile of the proposed algorithm for standard 6 bus ward-hale test system and IEEE-14 bus test system The figure shows that the algorithm is capable of obtaining a faster convergence for the three unit thermal system in a very few generations and the solution is consistent.

Test case 1: 6 bus ward-hale test system
Case study i
Method –i

Table 1. Load flow solution 1.5 times the base power.

Bus number	Bus voltage magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude(after load shedding)
3	0.792526	0.552319	-0.278049-j0.065721	0.299996	0.907653
4	0.821274	0.421552	0.00	0.230428	0.933661
5	0.761915	0.572051	-0.196304-j0.117783	0.299993	0.889731
6	0.788985	0.535638	-0.123482-j0.012348	0.294669	0.917190

Alpha: 1.5 Bcri: 0.3

Method –II

Table 2. Load flow solution 1.5 times the base power.

Bus number	Bus voltage magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude(after load shedding)
3	0.792526	0.565819	-0.272274-j0.064356	0.299995	0.905982
4	0.821274	0.427228	0.00	0.230818	0.931995
5	0.761915	0.589754	-0.190293-j0.114176	0.299906	0.887288
6	0.788985	0.537283	-0.121310-j0.012131	0.296168	0.915063

Alpha: 1.5 Bcri: 0.3

Case Study 2
Method I

Table 3. Load flow solution 1.1 times the base power.

Bus number	Bus voltage magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude (after load shedding)
3	0.910748	0.309107	-0.013415-j0.003171	0.299995	0.915424
4	0.929561	0.239028	0.00	0.231807	0.934368
5	0.891220	0.312879	-0.019480-j0.011688	0.298756	0.898976
6	0.911773	0.296007	0.00	0.286505	0.918155

Alpha: 1.1 Bcri: 0.3

Method II

Table 4. Load flow solution 1.1 times the base power.

Bus number	Bus voltage magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude(after load shedding)
3	0.910748	0.313655	-0.019744-j0.004430	0.299995	0.917204
4	0.929561	0.240298	0.00	0.229818	0.936187
5	0.891220	0.318878	-0.026911-j0.016146	0.298020	0.901871
6	0.911773	0.295298	0.00	0.281989	0.920540

Alpha: 1.1 Bcri: 0.3

Case Study 3
Method I

Table 5. Load flow solution 1.0 times the base power.

Bus number	Bus voltage magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude(after load shedding)
3	0.931663	0.268746	0.00	-	-
4	0.948248	0.208422	0.00	-	-
5	0.914858	0.270784	0.00	-	-
6	0.933040	0.257166	0.00	-	-

Alpha: 1.0 Bcri: 0.3

Method II

Table 6. Load flow solution 1.0 times the base power.

Bus number	Bus voltage magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude(after load shedding)
3	0.931663	0.272399	0.00	-	-
4	0.948248	0.209258	0.00	-	-
5	0.914858	0.275604	0.00	-	-
6	0.933040	0.256247	0.00	-	-

Alpha: 1.0 Bcri: 0.3

Test Case 2: IEEE 14 Bus System
Case Study 1
Method I

Table 7. Load flow solution 1.75 times the base power.

Bus number	Bus voltage magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude (after load shedding)
6	0.885987	0.076577	0.00	0.065605	0.926245
7	0.861489	0.103337	0.00	0.068974	0.935048
8	0.903179	0.052732	0.00	0.045991	0.939599
9	0.826483	0.188466	-0.117981-j0.066389	0.116584	0.915637
10	0.817095	0.181116	0.00	0.116787	0.904157
11	0.835082	0.101553	0.00	0.068160	0.912634
12	0.832003	0.065987	0.00	0.046524	0.909214
13	0.825003	0.090781	0.00	0.056859	0.906149
14	0.797535	0.225521	-0.22901-j0.076913	0.100380	0.910447

Alpha: 1.75 Bcri : 0.12

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Method II

Table 8. Load flow solution 1.75 times the base power.

Bus number	Bus voltage magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude (after load shedding)
6	0.885987	0.071513	0.00	0.060637	0.919887
7	0.861489	0.101100	0.00	0.068528	0.923378
8	0.903179	0.048410	0.00	0.041661	0.933292
9	0.826483	0.187316	-0.112015-j0.063032	0.119214	0.901171
10	0.817095	0.18039	-0.001460-j0.0000941	0.119999	0.888367
11	0.835082	0.101179	0.00	0.070317	0.894098
12	0.832003	0.067257	0.00	0.049879	0.887929
13	0.825003	0.090801	0.00	0.059871	0.885136
14	0.797535	0.225110	-0.220811-j0.074098	0.105331	0.892381

Alpha : 1.75 Lcri : 0.12

Case study II
Method I

Table 9. Load flow solution 1.5 times the base power.

Bus number	Bus voltage magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude (after load shedding)
6	0.965883	0.056862	0.00	0.054954	0.968854
7	0.961972	0.071512	0.00	0.066872	0.965849
8	0.975622	0.039895	0.00	0.038464	0.978367
9	0.939840	0.126675	0.00	0117218	0.946047
10	0.932435	0.121099	0.00	0.113175	0.937631
11	0.944580	0.068419	0.00	0.064546	0.947266
12	0.944571	0.044103	0.00	0.041059	0.946053
13	0.937257	0.060500	0.00	0.054197	0.940925
14	0.918004	0.148539	-0.092214-j0.030944	0.119998	0.932353

Alpha : 1.5 Bcri : 0.12

Method II

Table 10. Load flow solution 1.5 times the base power.

Bus number	Bus voltage magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude (after load shedding)
6	0.965883	0.051551	0.00	0.050210	0.968655
7	0.961972	0.069175	0.00	0.064798	0.965592
8	0.975622	0.035267	0.00	0.034432	0.978183
9	0.939840	0.124902	0.00	0.115731	0.945636
10	0.932435	0.119784	0.00	0.112075	0.937287
11	0.944580	0.067704	0.00	0.063903	0.947088
12	0.944571	0.044896	0.00	0.041999	0.945956
13	0.937257	0.060239	0.00	0.054229	0.940652
14	0.918004	0.147165	-0.085875-j0.028817	0.119997	0.931398

Alpha : 1.5 Lcri : 0.12

Case Study III
Method I

Table 11. Load flow solution 1.25 times the base power.

Bus number	Bus voltage Magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude (after load shedding)
6	0.991775	0.045028	0.00	-	-
7	0.984258	0.056165	0.00	-	-
8	1.000579	0.031853	0.00	-	-
9	0.972796	0.098070	0.00	-	-
10	0.967549	0.093527	0.00	-	-
11	0.978900	0.052892	0.00	-	-
12	0.980368	0.034090	0.00	-	-
13	0.974269	0046519	0.00	-	-
14	0.956955	0.113685	0.00	-	-

Alpha : 1.25 Bcri : 0.1

Method II

Table 12. Load flow solution 1.25 times the base power.

Bus number	Bus voltage Magnitude (before load shedding)	B indicator (before load shedding)	Sheddable load	B indicator (after load shedding)	Bus voltage magnitude (after load shedding)
6	0.991775	0.040850	0.00	-	-
7	0.984258	0.054596	0.00	-	-
8	1.000579	0.027980	0.00	-	-
9	0.972796	0.097214	0.00	-	-
10	0.967549	0.092971	0.00	-	-
11	0.978900	0.052608	0.00	-	-
12	0.980368	0.034715	0.00	-	-
13	0.974269	0.046498	0.00	-	-
14	0.956955	0.113325	0.00	-	-

Alpha : 1.25 Lcri : 0.12

Table 13. Computation time in sec for 6 bus Ward-Hale test system.

Cases	Computation time (secs.)	
	Method I	Method II
Case 1	0.66	0.82
Case 2	0.61	0.66
Case 3	0.22	0.27

Table 14. Computation time in sec for IEEE-14 bus system.

Cases	Computation time (secs.)	
	Method I	Method II
Case 1	1.21	1.42
Case 2	0.88	1.15
Case 3	0.49	0.55

7. Conclusions

A simple new method is developed to determine the optimum location and the optimum quantity of load to be shed in order to prevent the system voltage from going to the unstable. This method is based on indicators of risk of voltage instability. It can be implemented for large power system to estimate voltage instability. Successive load flow runs are required to accomplish this method. The proposed method can be used for real time applications in power systems. The computation speed of these indicators is fast compared to other methods.

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