ARTICLE IN PRESS
Ain Shams Engineering Journal (2016) xxx, xxx–xxx

Ain Shams University
Ain Shams Engineering Journal
www.elsevier.com/locate/asej
www.sciencedirect.com

ELECTRICAL ENGINEERING

Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth

Atma Ram Gupta *, Ashwani Kumar [1]

Department of Electrical Engineering, National Institute of Technology, Kurukshetra, Haryana 136119, India

Received 5 January 2016; revised 28 April 2016; accepted 29 May 2016

KEYWORDS

Mesh distribution system;
Load model;
D-STATCOM;
Sensitivity indices;
Loss reduction;
Annual energy savings

Abstract In this paper, an approach for optimal placement of D-STATCOM in mesh distribution systems using sensitivity approaches is proposed. The main contributions of the paper are as follows: (i) Optimal D-STATCOM placement based on the new voltage sensitivity index in mesh distribution system, (ii) optimal D-STATCOM size determination for seasonal loads with load growth scenario, (iii) comparison of D-STATCOM placement and size determination with the existing sensitivity methods, and (iv) impact of optimal D-STATCOM placement on voltage stability margin enhancement, energy loss reduction and cost of energy savings.

The results of voltage profile improvement, reduction in power losses, reduction in cost of energy loss, improved voltage stability margin, cost of energy loss savings, installation cost of D-STATCOM and annual savings are obtained for UK 38 bus practical mesh distribution system.

1. Introduction

Electric power distribution is the part of the power delivery infrastructure that takes the electricity from high-voltage transmission circuits and delivers it to the customers. Unlike transmission systems distribution systems have high R/X ratio which results in high power loss and may lead to voltage instability. Studies have indicated that 13% of total power generated is wasted in line losses at the distribution level [1]. Series voltage regulator and shunt capacitors are the two conventional ways of maintaining voltages of the distribution system within acceptable range. But, these devices have some disadvantages that are conventional series voltage regulators cannot generate reactive power and have slow response because of their step by step operations and shunt capacitors are unable to generate continuous variable reactive power and its natural oscillatory behavior with inductive components [2]. The D-FACTS devices can play an important role to overcome these problems with efficiently reducing the line power losses, correcting power factor, and improving voltage profile

* Corresponding author. Tel.: +91 1744233407 (Office), mobile: +91 9896279046.
E-mail addresses: arguptanitd@gmail.com (A.R. Gupta), ashwa_ks@yahoo.co.in (A. Kumar).
[1] Tel.: +91 1744233389 (Office), mobile: +91 9416366091; fax: +91 1744238050.
Peer review under responsibility of Ain Shams University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.asej.2016.05.009
2090-4479 © 2016 Faculty of Engineering, Ain Shams University. Production and hosting by Elsevier B.V.

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

of the power system. The D-STATCOM (Distribution STATCOM), a shunt connected voltage source converter has been utilized to increase the reliability and efficiency of distribution systems by providing reactive power support to improve the voltage profile and to reduce the line losses. Research work is being carried out by many researchers for finding the optimal location and sizes of D-FACTS devices. Hosseini and Shayanfar [3] derived the mathematical modeling and found the best location of D-STATCOM and SSVR for under voltage problem mitigation in the distribution network. Hussain and Visali [4] derived the voltage stability indicator for finding optimal bus for D-STATCOM placement in radial distribution system. Taher and Afsari [5] proposed immune algorithm for optimal location and sizing of D-STATCOM. Devi and Geethanjali [6] determined the location and size of D-STATCOM by using particle swarm optimization algorithm. Hussain and Subbaramiah [7] calculated the optimal size by mathematical modeling of D-STATCOM, to maintain the voltage magnitude as 1 p.u. and to supply the required reactive power for compensation at the node where D-STATCOM is placed. Farhoodnea et al. [8] used Firefly algorithm to determine the optimal size and location of D-STATCOM. Tolabi et al. [9] proposed ant colony algorithm and its combination with fuzzy multi-objective approach for simultaneous placement of DG and D-STATCOM in the reconfigured network. Yuvaraj et al. [10] proposed bat algorithm for D-STATCOM allocation in radial distribution networks considering load variations. Devabalaji and Ravi [11] used bacterial foraging optimization algorithm for finding optimal size and siting of multiple DG and DSTATCOM in Radial Distribution System (RDS). Exhaustive search method is proposed to find the optimal size of D-STATCOM in RDS [12]. Recently many algorithms such as Harmony search algorithm [13], improved cat swarm optimization [14] and variational algorithm [15] are used for D-STATCOM placement in balanced RDS with an objective of improving voltage profile and reducing losses. Impact of load model on D-STATCOM placement is explained in [16].

Many researchers have focused on analysis of radial distribution system with time invariant load models. However, the load on the system is time varying and the study of the time variant load model is essential for better distribution system planning. Also, wherever high reliability is required, distribution utilities are planning for mesh distribution networks. The mesh distribution system also needs to be analyzed with D-STATCOM placement with seasonal time varying loads. Additionally, the realistic load model which consists of residential, commercial and industrial loads shall be taken into account in this system study.

In this paper, optimal placement of D-STATCOM in mesh distribution system is presented using sensitivity approaches with seasonal (summer and winter) time varying realistic loads. A new stability index is proposed for optimal allocation of D-STATCOM. Load growth is also considered in this study which is an essential parameter while planning and expansion of the system. Annual energy savings, reduction in cost of energy loss, improved voltage profile and enhanced voltage stability margin are determined with D-STATCOM in the mesh distribution network. Load flow analysis for mesh distribution networks is presented in [17,18]. The mathematical equation used for load flow analysis of mesh distribution networks in this paper is taken from [19].

The rest of the paper is organized as follows: The mathematical modeling of D-STATCOM is given in Section 2. Section 3 explains the sensitivity approaches for finding optimal location of D-STATCOM. Section 4 deals with the variational algorithm to determine D-STATCOM size. In Section 5 realistic load model, model of load growth, cost of energy loss and cost of D-STACOM are presented. The proposed method is tested on standard UK 38-bus mesh distribution system and the results are presented in Section 6.

2. Modeling of D-STATCOM

The D-STATCOM is shown in Fig. 1 and its static model has been utilized for the distribution system load flow analysis. Since the device supports the reactive power at the connected bus, the voltage profile of the bus where the device is connected will improve and voltage at the buses will also be improved due to the reactive power support and the losses reduction. Thus, the D-STATCOM will also impact the voltages of the neighboring buses. The new voltages are V'_n at the candidate bus and V'_m at the previous bus. The current I'_m is summation of I_m and I_{DS}. Here I_{DS} is the current injected by D-STATCOM and is in quadrature with the voltage. Therefore, the expression for new voltage after installing D-STATCOM is given as below [5]:

$$V'_n\angle\theta'_n = V'_m\angle\theta'_m - (R_m + jX_m)(I_m\angle\delta) - (R_m + jX_m)\left(I_{DS}\angle\left(\frac{\pi}{2} + \theta'_n\right)\right) \quad (1)$$

By separating real and imaginary parts of (1), we obtain the equation of the form as follows:

$$t = \frac{-B \pm \sqrt{D}}{2A} \quad (2)$$

where,

$$t = \sin\theta'_n \quad (3)$$

$$A = (h_1h_3 - h_2h_4)^2 + (h_1h_4 + h_2h_3)^2 \quad (4)$$

$$B = 2(h_1h_3 - h_2h_4)\cdot(V'_n)(h_4) \quad (5)$$

$$C = (V'_n \cdot R_m)^2 - (h_1h_4 + h_2h_3)^2 \quad (6)$$

$$D = B^2 - 4AC \quad (7)$$

where,

$$h_1 = \text{real}(V'_m\angle\theta'_m) - \text{real}(Z_m \cdot I_m\angle\delta) \quad (8)$$

$$h_2 = \text{imag}(V'_m\angle\theta'_m) - \text{imag}(Z_m \cdot I_m\angle\delta) \quad (9)$$

$$h_3 = -X_m \quad (10)$$

$$h_4 = -R_m \quad (11)$$

Now, there are two roots of t. For determining the correct value of root, the boundary conditions are taken as follows:

$$V'_n = V_n \Rightarrow I_{DS} = 0 \;\; \& \;\; \theta'_n = \theta_n$$

Result show that $t = \frac{-B+\sqrt{D}}{2A}$ is the desired root of the Eq. (1). Therefore, the phase angle and magnitude of D-STATCOM current and reactive power injected to the system by the D-STATCOM are given by the expressions:

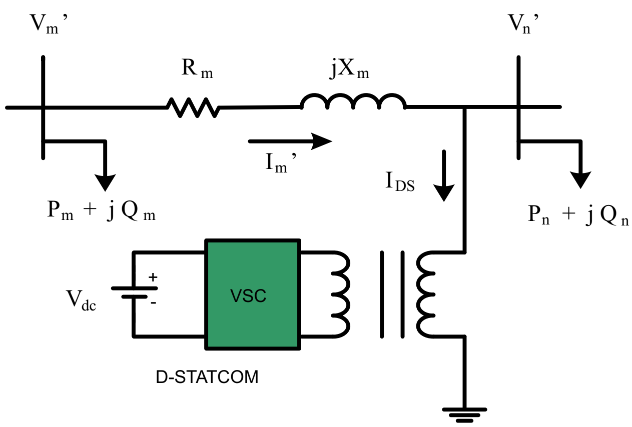

Figure 1 Single line diagram of 2-bus distribution system with D-STATCOM.

$$\angle I_{DS} = \frac{\pi}{2} + \theta'_n = \frac{\pi}{2} + \sin^{-1} t \tag{12}$$

$$|I_{DS}| = \frac{V'_n \cos\theta'_n - h_1}{-h_4 \sin\theta'_n - h_3 \cos\theta'_n} \tag{13}$$

$$jQ_{DS} = (V'_n \angle \theta'_n) \cdot \left(I_{DS} \angle \left(\frac{\pi}{2} + \theta'_n \right) \right)^* \tag{14}$$

where * denotes the complex conjugate.

3. Sensitivity indices for optimal location of D-STATCOM placement in mesh distribution system

In this work, following sensitivity indices are used for finding best location of D-STATCOM.

a. Fast Voltage Stability Index (FVSI)
b. Combined Power Loss Sensitivity (CPLS)
c. Voltage Stability Index (VSI)
d. Voltage Sensitivity Index (VSEI)
e. Proposed Stability Index (PSI).

3.1. Fast voltage stability index

FVSI between sending and receiving node is expressed in [20]:

$$\text{FVSI} = \frac{4Z_{ij}^2 Q_j}{V_i^2 X_{ij}} \tag{15}$$

where Z is the line impedance magnitude, X is the line reactance, Q_j is the receiving end reactive power, V_i is the sending end voltage.

The bus with high FVSI value is more sensitive toward instability. Hence, the bus that provides highest value of FVSI will be selected as optimal bus for D-STATCOM placement.

3.2. Combined power loss sensitivity

D-STATCOM placement affects both real and reactive power losses. Therefore both real and reactive power losses are considered for finding CPLS as follows [21]:

$$\frac{\partial Ploss}{\partial Q_2} = \frac{2 * Q_{2*R[j]}}{V_2^2} \tag{16}$$

$$\frac{\partial Qloss}{\partial Q_2} = \frac{2 * Q_{2*X[j]}}{V_2^2} \tag{17}$$

Combined loss sensitivity with respect to reactive power

$$= \frac{\partial Sloss}{\partial Q_2} = \frac{\partial ploss}{\partial Q_2} + j\frac{\partial Qloss}{\partial Q_2} \tag{18}$$

Combined loss sensitivity with respect to real power

$$= \frac{\partial Sloss}{\partial P_2} = \frac{\partial ploss}{\partial P_2} + j\frac{\partial Qloss}{\partial P_2} \tag{19}$$

$$\text{Loss sensitivity matrix} = \begin{vmatrix} \frac{\partial ploss}{\partial P_2} & \frac{\partial Qloss}{\partial P_2} \\ \frac{\partial ploss}{\partial Q_2} & \frac{\partial Qloss}{\partial Q_2} \end{vmatrix} \tag{20}$$

Loss sensitivity matrix is obtained using power flow analysis and the bus that provides highest value of CPLS will be selected as optimal bus for D-STATCOM placement.

3.3. Voltage stability index

Voltage stability index between sending and receiving node is derived with modification (without neglecting the line resistance due to high R/X ratio of distribution systems) of VSI used for transmission network as given in [22]:

$$\text{VSI} = 4\left[Q_2 X + \frac{Q_2 R^2}{X}\right] \frac{[1 - \cos 2\emptyset]}{2V_1^2 \sin^2(\delta_1 - \delta_2 - \emptyset)} \tag{21}$$

The value of VSI is for normal loading condition should be less than one. For critical loading its value reaches to one. Hence, the bus that provides highest value of VSI will be selected as optimal bus for D-STATCOM placement.

3.4. Voltage sensitivity index

Voltage sensitivity index is derived in [23]

$$\text{VSEI} = \frac{4X}{V_1^2}\left(\frac{P_2^2}{Q_2} + Q_2\right) \leqslant 1 \tag{22}$$

The VSEI values are less than unity for normal operating conditions. The bus having the highest value of VSEI is more susceptible to stability. Hence, the bus that provides highest value of VSEI will be selected as optimal bus for D-STATCOM placement.

3.5. Proposed stability index

The equivalent circuit model of distribution system is shown in Fig. 2 and the mathematical model of the proposed stability index is given below:

The branch current I_{ij} can be calculated using Eq. (23).

$$I_{ij} = \left[\frac{P_j + jQ_j}{V_j \angle \delta}\right]^* \tag{23}$$

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

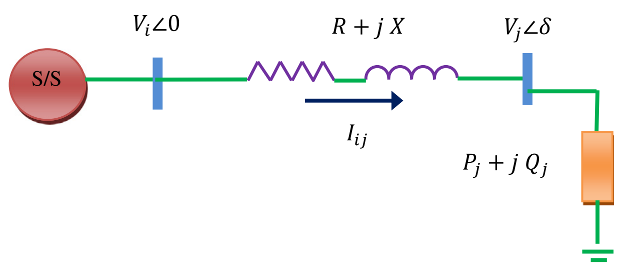

Figure 2 Equivalent circuit model of RDS.

The receiving end bus voltage can be written as follows:

$$V_j\angle\delta = V_i\angle 0 - (R + jX)I_{ij} \tag{24}$$

Substitute Eq. (23) in Eq. (24),

$$V_j\angle\delta = V_i\angle 0 - (R + jX)\left[\frac{P_j + jQ_j}{V_j\angle\delta}\right]^* \tag{25}$$

$$V_j\angle\delta = V_i\angle 0 - (R + jX)\left[\frac{P_j - jQ_j}{V_j\angle - \delta}\right] \tag{26}$$

$$V_j^2 = V_iV_j\angle - \delta - (R + jX)(P_j - jQ_j) \tag{27}$$

$$V_j^2 = V_iV_j\cos\delta - jV_iV_j\sin\delta - (R + jX)(P_j - jQ_j) \tag{28}$$

$$V_j^2 + \left[P_jR + Q_jX + j(P_jX - Q_jR)\right] = V_iV_j\cos\delta - jV_iV_j\sin\delta \tag{29}$$

Separate real and imaginary parts in Eq. (29).

$$V_j^2 + P_jR + Q_jX = V_iV_j\cos\delta \tag{30}$$

$$P_jX - Q_jR = -V_iV_j\sin\delta \tag{31}$$

Let $\delta \approx 0$

$$V_j^2 + P_jR + Q_jX = V_iV_j \tag{32}$$

$$P_jX - Q_jR = 0 \tag{33}$$

$$X = \frac{Q_jR}{P_j} \tag{34}$$

Substitute Eq. (34) in Eq. (30),

$$V_j^2 + P_jR + Q_j\frac{Q_jR}{P_j} = V_iV_j \tag{35}$$

$$V_j^2 - V_jV_i + \left(\frac{Q_j^2}{P_j} + P_j\right)R = 0 \tag{36}$$

For stable bus voltage, $b^2 - 4ac \geqslant 0$.
The new stability index can be obtained as follows:

$$V_i^2 - 4\left(\frac{Q_j^2}{P_j} + P_j\right)R \geqslant 0 \tag{37}$$

$$1 \geqslant \frac{4R}{V_i^2}\left(\frac{Q_j^2}{P_j} + P_j\right) \tag{38}$$

$$\text{PSI} = \frac{4R}{V_i^2}\left(\frac{Q_j^2}{P_j} + P_j\right) \leqslant 1 \tag{39}$$

Under normal operating conditions, PSI value should be less than unity. If the value of PSI is closer to zero, then the system is more stable. If the value of PSI is high, then the system is vulnerable to instability. Thus the bus with high PSI value is more sensitive and it is selected for optimal D-STATCOM placement.

4. Mathematical model of load, load growth, cost of energy loss and D-STATCOM cost

4.1. Load growth

The load growth is represented as follows:

$$\text{Load}_i = \text{Load} \times (1 + r)^m \tag{40}$$

r = annual growth rate, m = plan period up to which feeder can take the load. In this paper, r = 10% and m = 5.

4.2. Cost of Energy Loss (CEL)

The cost of energy loss has been determined using Eq. (41)

$$\text{CEL} = (\text{Total Real power Loss}) * (E_c * T)\ \$ \tag{41}$$

E_c: energy rate (\$/kW h), T: time duration (h), $E_c = 0.06$ \$/kW h, $T = 8760$ h.

4.3. Load model

Load is time varying and it is combination of residential, industrial and commercial load. Let α, β and γ be the percentages of residential, commercial and industrial load at each bus respectively. The realistic load model is mathematically represented by Eqs. (42) and (43). In this paper work, summer and winter loads are considered for the analysis.

$$P = P_o\left[\alpha\left(\frac{V}{V_o}\right)^{n_{pr}} + \beta\left(\frac{V}{V_o}\right)^{n_{pc}} + \gamma\left(\frac{V}{V_o}\right)^{n_{pi}}\right] \tag{42}$$

$$Q = Q_o\left[\alpha\left(\frac{V}{V_o}\right)^{n_{qr}} + \beta\left(\frac{V}{V_o}\right)^{n_{qc}} + \gamma\left(\frac{V}{V_o}\right)^{n_{qi}}\right] \tag{43}$$

P_o and Q_o are the real and reactive power consumed at a reference voltage V_o. The exponent values and load compositions for each load type are given in [25].

4.4. Cost of D-STATCOM

The cost of reactive power supported by the D-STATCOM is also determined using Eq. (44). Since the reactive support is identified as important ancillary services and the devices providing this support can be remunerated based on their reactive support. The cost can be paid to the devices based on the cost savings obtained due to the reduction in the loss with D-STATCOM.

$$\text{Cost}_{\text{D-STATCOM}} = \text{Investment\_cost}_{\text{D-STATCOM}} \times \frac{[1 + B]^{nDST} * B}{[1 + B]^{nDST} - 1} \tag{44}$$

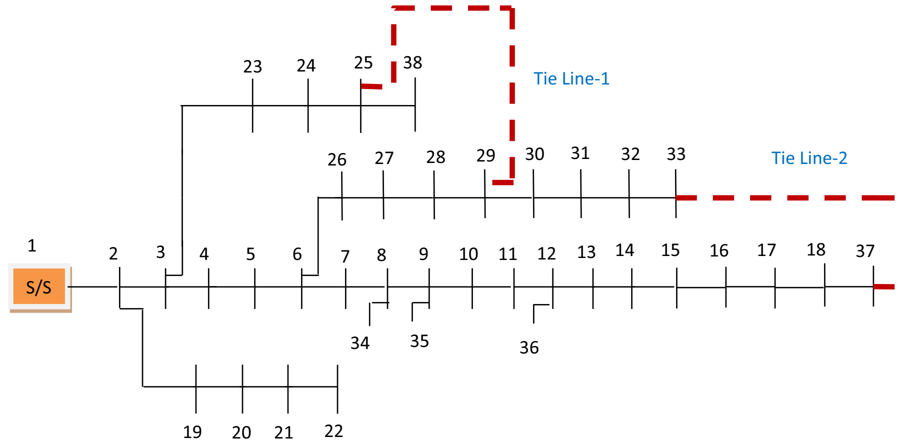

Figure 3 Single line diagram of 38 bus mesh distribution network.

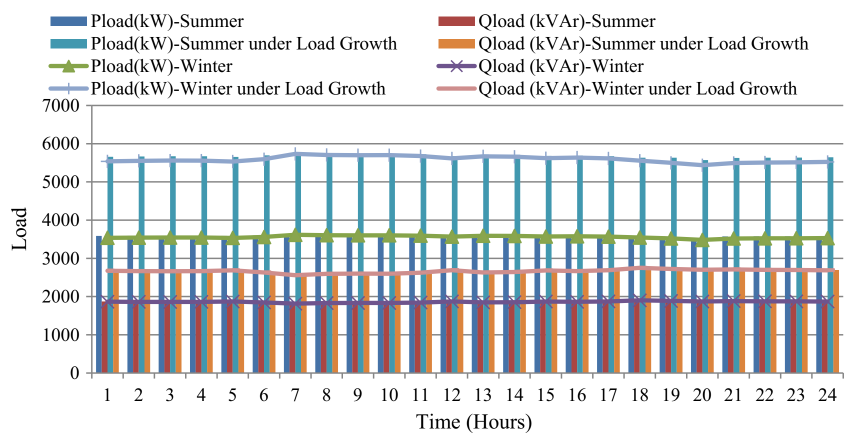

Figure 4 Load profile for 38-bus mesh distribution network.

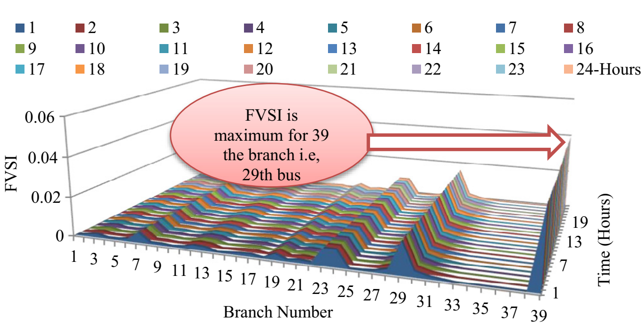

Figure 5 FVSI profile for 38-bus mesh distribution system.

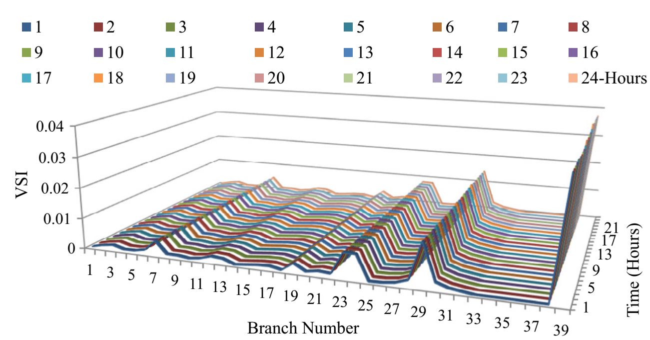

Figure 6 VSI profile for 38-bus mesh distribution system.

nDST: the longevity of DSTATCOM in years, *B*: is the asset rate of return.

$\text{Investment}_{\text{cost}} = 50\ \$/\text{kVAr},\ B = 0.1,\ nDST = 30$ years.

4.5. Voltage Stability Margin (VSM)

Voltage stability margin [28] is determined for each bus using Eq. (45). The VSM improvement has been determined with D-STATCOM and the results are compared for VSM enhancement at each bus. VSM of each bus is a number between 0 and 1.

$$\begin{aligned}\text{VSM}(re(i)) = {} & V(se(i))^4 - 4(P(i)x(i) - Q(I)r(i))^2 \\ & - 4(V(se(i))^2(P(i)r(i) + Q(i)x(i)) \qquad (45)\end{aligned}$$

where, P = is the sum of the real power loads of all the nodes beyond each node, plus the real power load at each node itself, plus the sum of real power losses of all branches beyond each node, Q = is the sum of the reactive power loads of all the

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

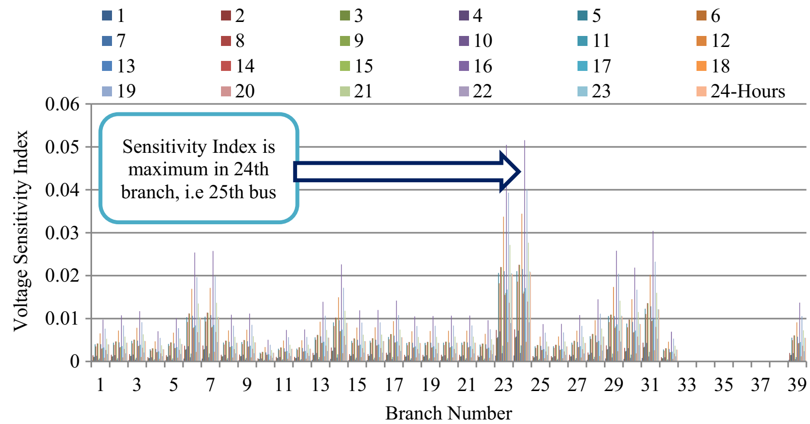

Figure 7 VESI profile for 38-bus mesh distribution system.

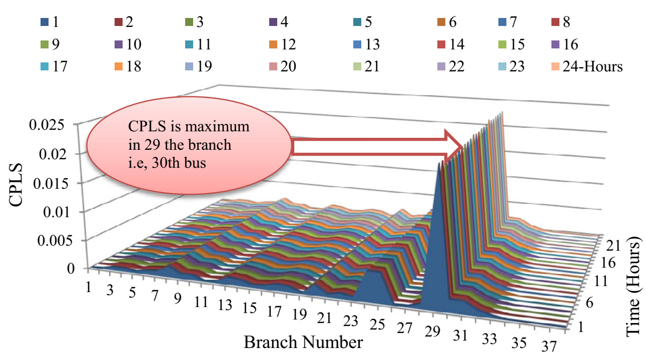

Figure 8 CPLS profile for 38-bus mesh distribution system.

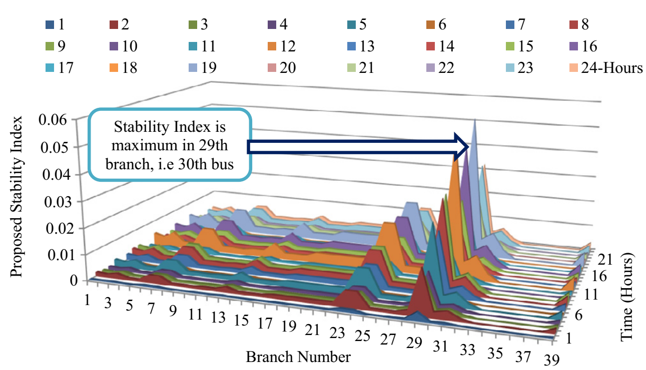

Figure 9 Proposed stability index profile for 38-bus mesh distribution system.

nodes beyond each node, plus the reactive power load at each node itself, plus the sum of reactive power losses of all branches beyond each node.

5. Optimal D-STATCOM size determination using variational algorithm

The optimal size of D-STACOM is obtained based on the following algorithmic steps:

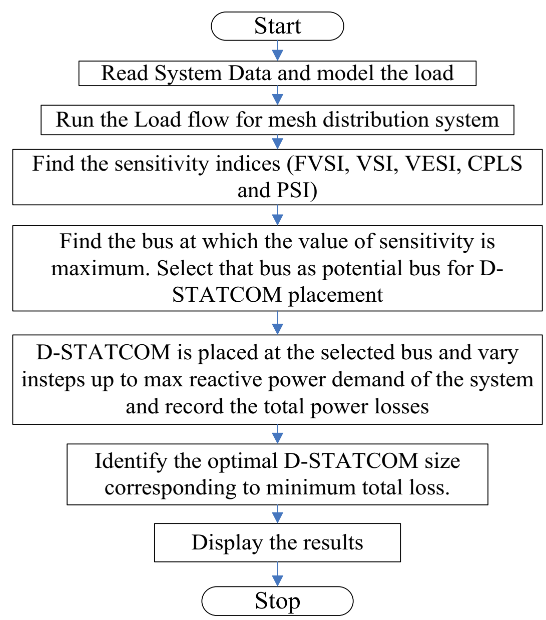

Figure 10 Flowchart for finding the results for all cases.

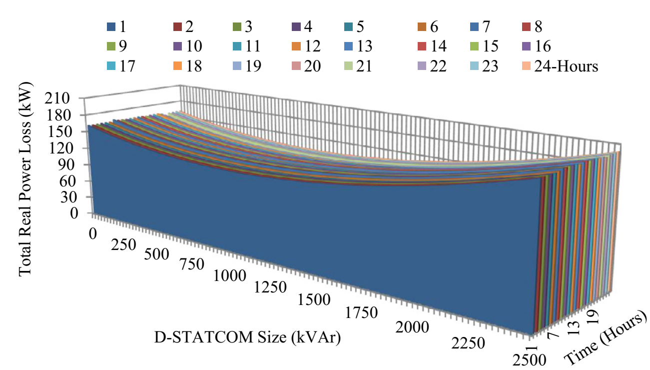

Figure 11 Real power loss variation with D-STATCOM at 30th bus for summer without load growth.

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

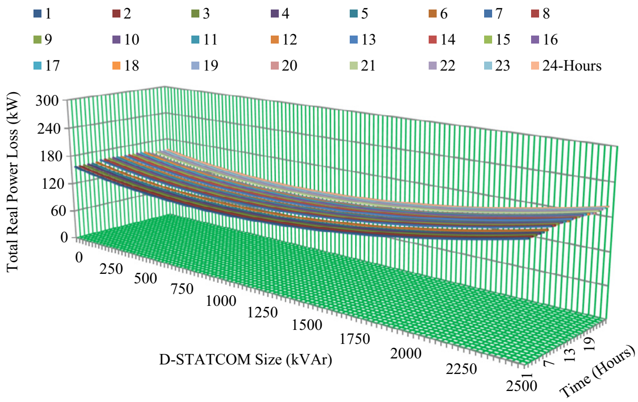

Figure 12 Real power loss variation with D-STATCOM at 30th bus for winter without load growth.

i. First, place the D-STATCOM at the bus based on sensitivity indices described in Section 3.
ii. Vary D-STATCOM size from a minimum value to a value equal to feeder reactive loading capacity in constant steps until the minimum system losses are obtained.
iii. Choose the D-STATCOM size that resulted in the minimum losses in the network.
iv. With the obtained size, run the load flow to obtain the results.
v. Plot all results and stop.

6. Results and discussions

The results are obtained for UK 38-bus mesh distribution system [24] with realistic 24 h time varying load [25] without and with D-STATCOM. Base kV of 12.66 kV and base MVA of 1 MVA are used. Two loops have taken in this study, loop-1 between buses 25 and 29 tie line impedance equal to $0.0473 + j^{*}0.16$ p.u. and loop-2 between buses 33 and 37 tie line impedance equal to $0.0473 + j^{*}0.16$ p.u. The distribution network consists of two loops as shown in Fig. 3 [26]. The analysis has been carried out in MATLAB version 7.8 on Windows 8 Intel® Core™ i7 Processor, 1.8 GHz, RAM 8 GB. The load profile for the 38 bus mesh distribution network in summer and winter seasons under load growth scenario is shown in Fig. 4. Average load (kVA) on the system is

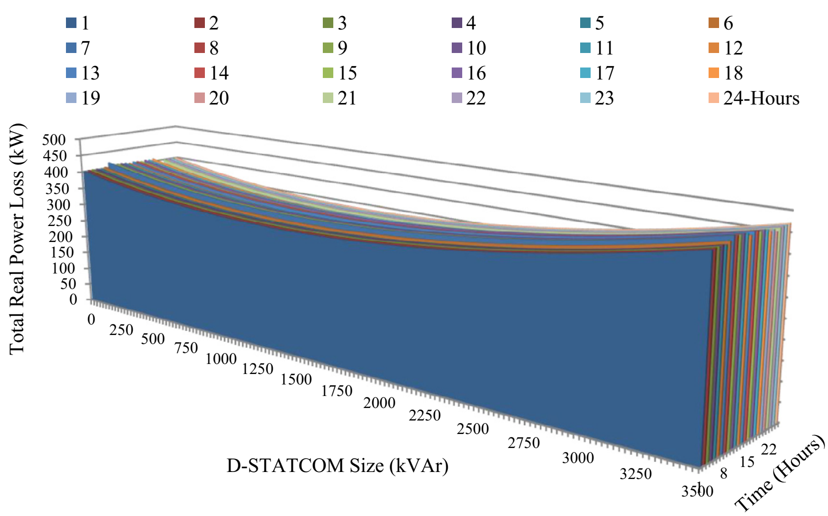

Figure 13 Real power loss variation with D-STATCOM at 30th bus in summer with load growth.

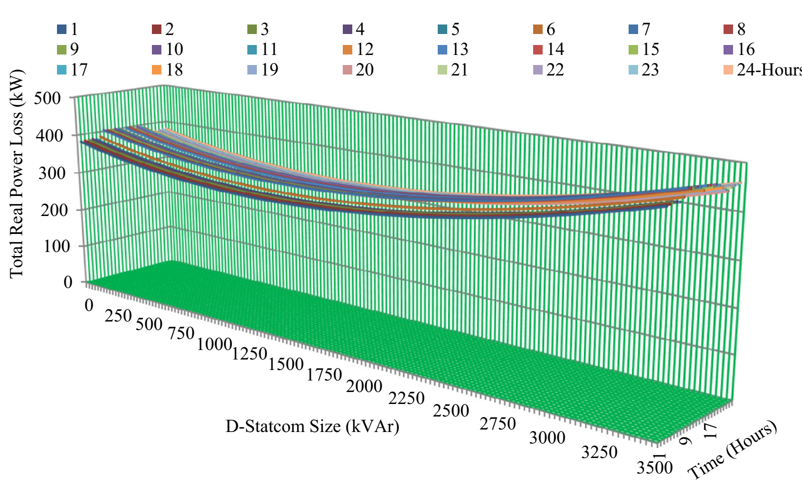

Figure 14 Real power loss variation with D-STATCOM at 30th bus for winter with load growth.

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

Table 1 Optimal D-STATCOM sizes (KVAR) for 38-bus mesh distribution system.

Time (h)	CPLS, proposed stability index (at 30th bus)				Voltage sensitivity index (at 25th bus)				FVSI, VSI (at 29th bus)			
	Summer without load growth	Winter without load growth	Summer with load growth	Winter with load growth	Summer without load growth	Winter without load growth	Summer with load growth	Winter with load growth	Summer without load growth	Winter without load growth	Summer with load growth	Winter with load growth
1	975	950	1350	1325	525	525	775	775	1000	975	1400	1375
2	950	950	1350	1325	525	525	775	750	1000	975	1400	1375
3	950	950	1350	1325	525	525	775	775	1000	975	1400	1375
4	950	950	1350	1325	525	525	775	775	1000	975	1400	1375
5	975	950	1375	1325	525	525	800	775	1000	975	1400	1375
6	950	950	1350	1325	525	525	775	775	975	975	1400	1350
7	950	925	1350	1325	525	525	775	775	1000	975	1400	1350
8	950	950	1325	1325	525	525	775	775	975	975	1375	1375
9	950	950	1300	1325	525	525	775	775	975	975	1375	1375
10	950	950	1325	1325	525	525	775	775	975	975	1375	1375
11	950	950	1350	1325	525	525	775	775	975	975	1400	1375
12	975	950	1375	1350	525	525	775	775	1000	1000	1425	1375
13	950	950	1350	1350	525	525	775	775	1000	975	1400	1375
14	950	950	1350	1350	525	525	775	775	1000	975	1400	1400
15	975	950	1350	1350	525	525	800	775	1000	1000	1425	1400
16	975	950	1375	1350	525	525	800	775	1000	975	1425	1400
17	975	950	1375	1350	525	525	800	775	1000	1000	1425	1400
18	975	950	1425	1375	550	525	800	800	1025	1000	1475	1425
19	975	950	1375	1350	525	525	775	775	1000	1000	1450	1375
20	950	950	1375	1325	525	525	775	775	1000	975	1400	1375
21	975	950	1375	1325	525	525	775	775	1000	975	1425	1375
22	975	950	1375	1325	525	525	775	775	1000	975	1425	1375
23	975	950	1375	1325	525	525	800	750	1000	975	1425	1375
24	975	950	1375	1325	525	525	800	775	1000	975	1400	1375

$3594.38 + j1865.51$ in summer, $3558.1 + j1861.18$ in winter, $5678.59 + j2668.59$ in summer and $5591.28 + j2664.30$ in winter with load growth. From Fig. 4, it can be observed that both real and reactive power demand in summer load is slightly higher in summer season than in the winter season. Load profile shows that peak real and reactive power demands are appearing at 7th and 18th hours in a day respectively. Residential load is high on the network at early mornings and mid nights.

Voltage sensitivity profiles for all the indices (FVSI, VSI, VESI, CPLS and PSI) are obtained and are shown in Figs. 5–9 for summer load and are also obtained for other loads but the results are shown for summer load only. It can be observed from Figs. 5–9 that FVSI and VSI are maximum for 39th line (29th bus), CPLS and proposed stability index are maximum for 29th line (30th bus) and VESI is maximum for 24th line (25th bus) for optimal placement of D-STATCOM. Based on all the sensitivity indices, 25th, 29th and 30th are most suitable buses for 38-bus mesh distribution system. The complete steps for finding the results are explained using flowchart shown in Fig. 10.

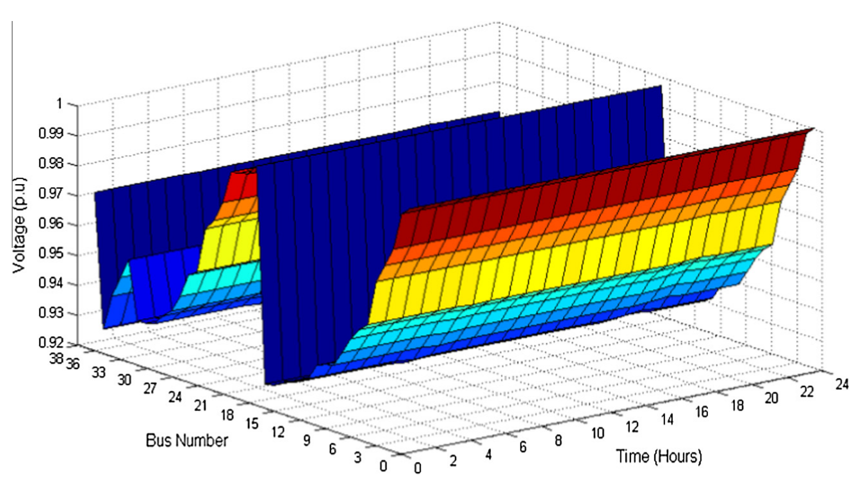

Figure 15 Base case voltage profile in summer without load growth.

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

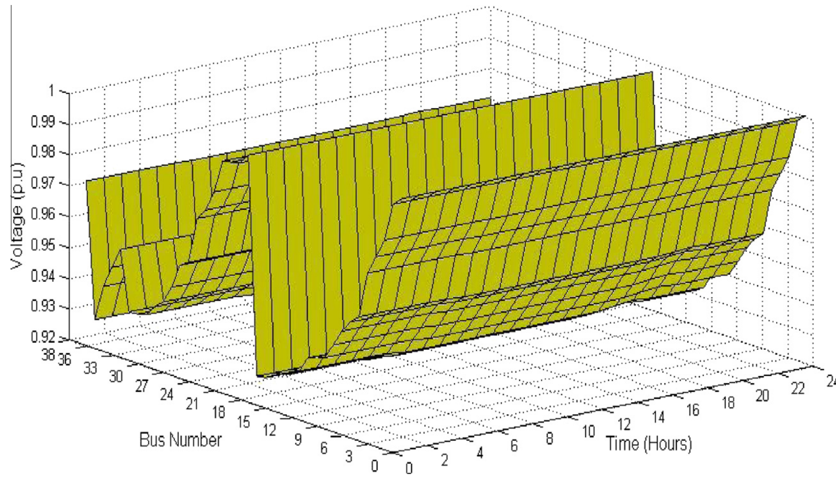

Figure 16 Base case voltage profile in winter without load growth.

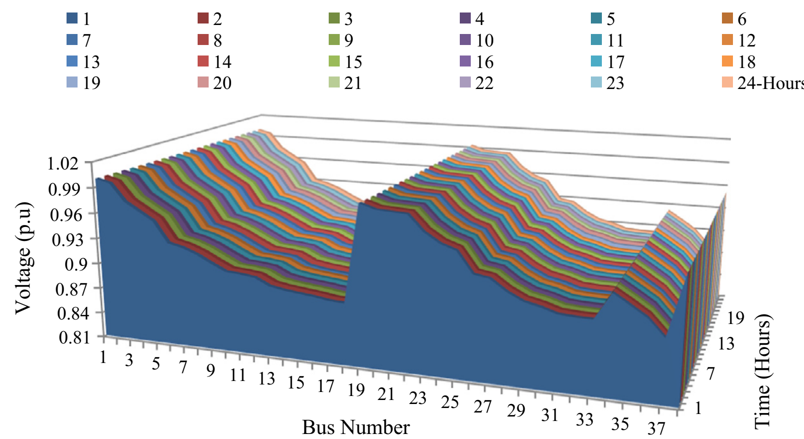

Figure 17 Base case voltage profile in summer with load growth.

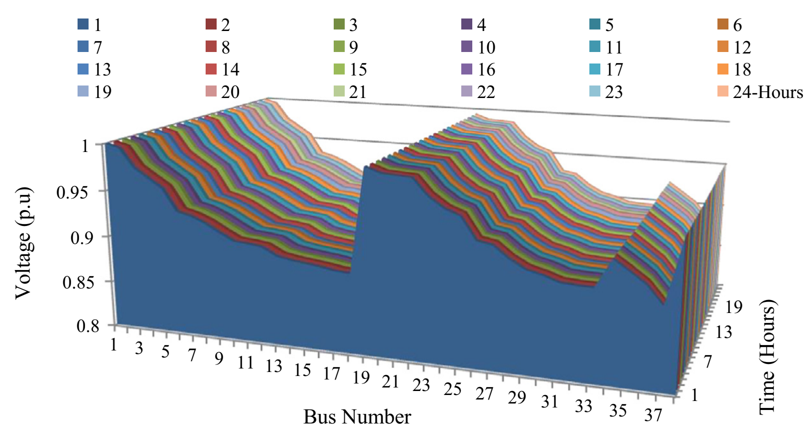

Figure 18 Base case voltage profile for winter with load growth.

The following cases are considered in this paper work:

Case A: Optimal D-STATCOM placement in summer load without load growth
Case B: Optimal D-STATCOM placement in winter load without load growth
Case C: Optimal D-STATCOM placement in summer load with load growth
Case D: Optimal D-STATCOM placement in winter load with load growth

Total real power loss variation with respect to D-STATCOM size for all cases is obtained by placing the D-STATCOM at 25th, 29th and 30th bus. Total real power loss variation with respect to D-STATCOM size for all cases is graphically represented in Figs. 11–14 after placement of

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

Table 2 Minimum voltage and minimum VSM without installation of D-STATCOM.

Time (h)	Min voltage (p.u.)				Min voltage stability margin			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
1	0.92495	0.9262	0.88192	0.88504	0.73193	0.73591	0.60494	0.61354
2	0.92494	0.92614	0.88186	0.88486	0.73189	0.73572	0.60477	0.61305
3	0.92493	0.9261	0.88182	0.88473	0.73187	0.73558	0.60467	0.61271
4	0.92493	0.92609	0.88183	0.88472	0.73188	0.73555	0.60469	0.61266
5	0.92496	0.92618	0.88194	0.88499	0.73195	0.73583	0.60500	0.61340
6	0.92489	0.92595	0.88164	0.88429	0.73175	0.73511	0.60417	0.61147
7	0.92422	0.92506	0.87976	0.88181	0.72964	0.73228	0.59905	0.60465
8	0.92469	0.9251	0.88092	0.88197	0.73110	0.73240	0.60221	0.60507
9	0.92472	0.92511	0.88102	0.88202	0.73121	0.73245	0.60248	0.60522
10	0.92470	0.92511	0.88096	0.88201	0.73113	0.73244	0.60231	0.60519
11	0.92472	0.92517	0.88108	0.88223	0.73119	0.73263	0.60263	0.60579
12	0.92471	0.92533	0.88126	0.88281	0.73119	0.73314	0.60314	0.60738
13	0.92468	0.92519	0.88102	0.88230	0.73109	0.73269	0.60249	0.60599
14	0.92470	0.92521	0.88109	0.88239	0.73115	0.73277	0.60268	0.60623
15	0.92475	0.92531	0.88131	0.88274	0.73129	0.73308	0.60328	0.60719
16	0.92465	0.92528	0.88106	0.88262	0.73100	0.73297	0.60258	0.60686
17	0.92465	0.92533	0.88111	0.88282	0.73098	0.73315	0.60273	0.60742
18	0.92447	0.9255	0.88087	0.8834	0.73041	0.73367	0.60206	0.60901
19	0.92499	0.92628	0.88211	0.88533	0.73207	0.73617	0.60547	0.61436
20	0.92572	0.92708	0.88328	0.88666	0.73437	0.73872	0.60868	0.61805
21	0.92499	0.92639	0.88213	0.8856	0.73207	0.73652	0.60553	0.61510
22	0.92498	0.92637	0.88208	0.88552	0.73202	0.73645	0.60538	0.61487
23	0.92497	0.92635	0.88206	0.88546	0.73201	0.73639	0.60532	0.61471
24	0.92496	0.92629	0.88200	0.88528	0.73198	0.73618	0.60516	0.61421

D-STATCOM at 30th bus only. Optimal D-STATCOM sizes are given in Table 1 for seasonal loads without and with load growth. The standard D-STATCOM sizes are available in ratings up to ±10 MVAR in a single container, in increments of ±1.25 MVAR [27].

Voltage profiles for the mesh distribution network in the base case (without installation of D-STATCOM) are shown in Figs. 15–18 for summer and winter season loads without and with load growth consideration. The voltage is poor at the 18th and 37th buses. The impact of seasonal loads and load

Table 3 Real power loss and cost of energy loss in base case.

Time (h)	Total real power loss (kW)				Cost of energy loss ($)			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
1	204.43	198.44	504.64	481.04	107,450	104,300	265,240	252,830
2	204.49	198.67	505.13	482.18	107,480	104,420	265,500	253,430
3	204.52	198.84	505.44	482.97	107,500	104,510	265,660	253,850
4	204.51	198.88	505.39	483.04	107,490	104,530	265,630	253,890
5	204.4	198.55	504.49	481.26	107,430	104,360	265,160	252,950
6	204.68	199.41	506.88	485.98	107,580	104,810	266,420	255,430
7	207.3	202.94	518.91	502.25	108,960	106,670	272,740	263,980
8	205.51	202.74	511.84	500.73	108,020	106,560	269,020	263,180
9	205.37	202.67	511.17	500.27	107,940	106,520	268,670	262,940
10	205.47	202.68	511.55	500.36	108,000	106,530	268,870	262,990
11	205.37	202.42	510.49	498.68	107,940	106,390	268,310	262,110
12	205.32	201.77	508.54	494.42	107,920	106,050	267,290	259,870
13	205.48	202.34	510.68	498.17	108,000	106,350	268,410	261,840
14	205.4	202.24	510.12	497.48	107,960	106,300	268,120	261,480
15	205.2	201.84	508.32	494.9	107,850	106,090	267,170	260,120
16	205.56	201.98	509.99	495.81	108,040	106,160	268,050	260,600
17	205.57	201.75	509.41	494.35	108,050	106,040	267,750	259,830
18	206.28	201.14	510.29	490.43	108,420	105,720	268,210	257,770
19	204.25	198.15	503.2	478.95	107,350	104,150	264,480	251,740
20	201.18	194.84	495.27	470.38	105,740	102,410	260,310	247,230
21	204.26	197.73	503.01	477.44	107,360	103,930	264,380	250,940
22	204.31	197.81	503.41	478.02	107,390	103,970	264,590	251,250
23	204.33	197.88	503.57	478.38	107,400	104,010	264,680	251,440
24	204.37	198.12	504.02	479.52	107,420	104,130	264,910	252,040

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

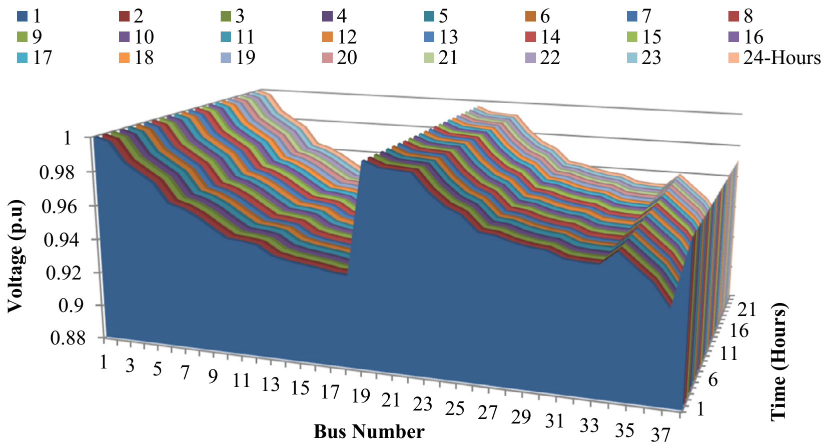

Figure 19 Voltage profile in summer with D-STACOM without load growth.

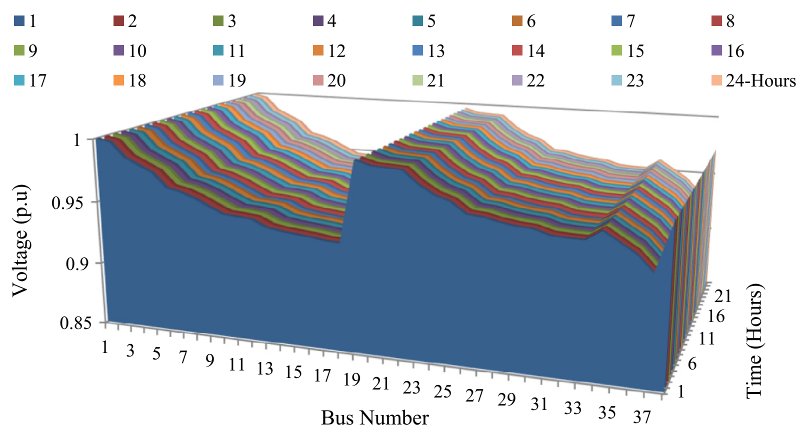

Figure 20 Voltage profile in winter with D-STACOM without load growth.

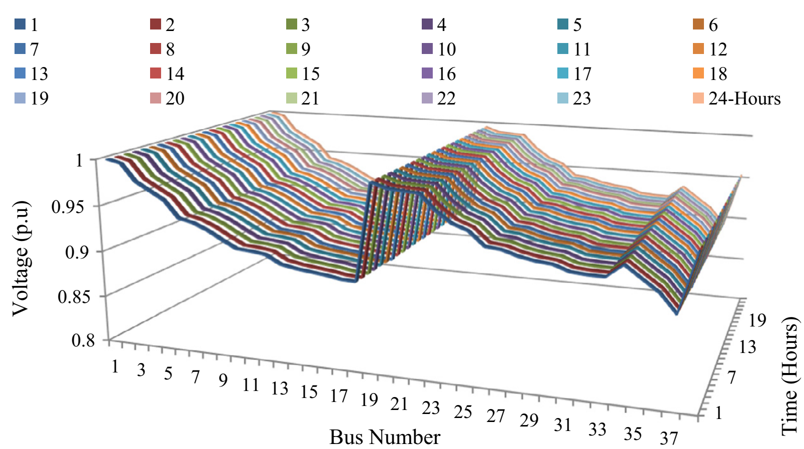

Figure 21 Voltage profile in summer with D-STACOM with load growth.

growth on the system performance without D-STATCOM is evaluated and results are given in Table 2 for minimum voltage and minimum voltage stability margin for each hour.

In Table 3, total real power loss and cost of energy loss in each hour are presented for base case i.e. without installation of D-STATCOM. As the load increases losses also increase. Loses are more in case C and case D compared to case A and case B in each hour as is observed from Table 3 due to the load increase. The D-STATCOM is installed at 25th bus (based on voltage sensitivity index), 29th bus (based on FVSI, VSI) and 30th bus (based on CPLS and proposed stability index) as different locations are obtained based on the differ-

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

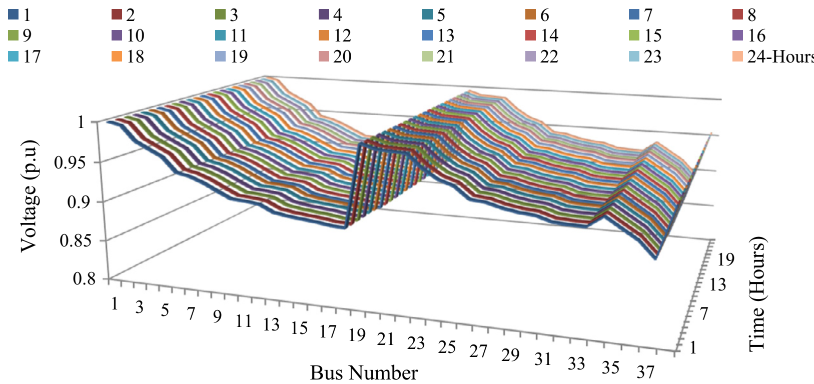

Figure 22 Voltage profile in winter with D-STATCOM with load growth.

Table 4 Cost of energy losses ($) after installation of D-STATCOM.

Ti me (h)	CPLS, proposed stability index (at 30th bus)				Voltage sensitivity index (at 25th bus)				FVSI, VSI (at 29th bus)			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
1	68,738	66,788	178446.45	170273.37	82,093	79,618	205246.8	195407.56	69,306	67,350	179686.87	171492.76
2	68,848	66,956	178935.26	160523.49	82,130	79,744	205530.62	196022.52	69,411	67,519	180165.16	172218.09
3	68,917	67,067	179250.62	157532.83	82,151	79,833	205709.32	196,443	69,479	67,624	180470.01	172670.11
4	68,911	67,051	179219.08	164349.86	82,146	79,849	205683.04	196469.28	69,469	67,608	180438.48	172607.04
5	68,717	66,746	178346.59	192059.49	82,078	79,665	205162.70	195486.40	69,285	67,308	179592.26	171303.55
6	69,216	67,550	180622.44	124199.28	82,256	80,154	206534.52	198082.87	69,773	68,097	181810.29	174735.72
7	70,493	69,584	186330.45	62178.48	83,628	82,030	212815.44	206697.45	71,035	70,110	187486.77	183550.03
8	69,900	69,222	183786.55	100436.90	82,724	81,899	209220.33	205814.44	70,441	69,763	184927.10	182004.76
9	69,815	69,137	183418.63	108378.72	82,651	81,857	208857.67	205556.90	70,357	69,679	184538.16	181615.82
10	69,847	69,158	183539.52	105671.88	82,698	81,867	209052.14	205609.46	70,388	69,700	184680.07	181710.43
11	69,610	68,848	182446.27	131158.22	82,624	81,710	208437.19	204668.64	70,162	69,400	183618.36	180359.64
12	69,027	68,049	179765.71	210350.37	82,545	81,321	207233.56	202282.41	69,600	68,617	181016.64	176874.91
13	69,574	68,764	182241.28	137270.95	82,672	81,662	208505.52	204384.81	70,120	69,316	183429.14	179970.69
14	69,463	68,633	181757.73	149906.37	82,624	81,599	208190.16	203995.87	70,015	69,190	182950.84	179397.79
15	69,069	68,134	179970.69	202765.96	82,493	81,363	207144.21	202545.21	69,637	68,701	181200.6	177232.32
16	69,274	68,328	180869.47	176848.63	82,682	81,447	208027.22	203065.56	69,836	68,890	182099.37	178068.02
17	69,074	68,049	179949.67	206308.51	82,666	81,310	207659.30	202245.62	69,647	68,617	181211.11	176853.88
18	68,664	67,314	177989.18	285027.62	82,961	80,948	207864.28	200048.61	69,258	67,892	179350.48	173647.72
19	68,444	66,299	177100.92	246411.79	81,978	79,429	204426.86	194193.43	69,017	66,872	178383.38	169432.41
20	66,972	64,838	173074.82	228793.68	80,385	77,726	200285.13	189762.62	67,540	65,400	174341.52	165458.88
21	68,375	66,210	176790.81	212657.76	81,978	79,224	204300.72	193447.08	68,953	66,783	178073.28	169059.24
22	68,459	66,352	177174.50	190162.08	82,009	79,276	204531.98	193783.46	69,038	66,919	178446.45	169647.91
23	68,496	66,410	177337.44	186698.37	82,020	79,313	204621.33	193983.19	69,069	66,977	178604.13	169884.43
24	68,601	66,567	177805.22	180086.32	82,051	79,444	204884.13	194592.88	69,169	67,135	179066.66	170567.71

ent sensitivity indices. Accordingly, optimal D-STATCOM sizes are obtained. It can be observed that required reactive power support obtained from D-STACTOM is varying with respect to time as per the load requirement.

Distribution system planning must provide accurate and efficient control of the reactive power for satisfactory operation of the distribution network. The improvement in voltage profile, improvement in voltage stability margin and reduction in power losses are more with CPLS and proposed stability index methods (i.e., with installation of D-STATCOM at 30th bus) than other sensitivity approaches. Voltage profiles after installation of D-STATCOM at 30th bus using CPLS and proposed stability index are depicted in Figs. 19–22 for summer and winter seasons with 24 h load variations.

After installation of D-STATCOM, there is significant reduction in power losses and thereby the cost of energy loss reduces. There is considerable improvement in the voltage stability margin. It can be understood that voltage profile with D-STATCOM installed at 30th bus is much better than with D-STATCOM installed at 25th bus and 29th bus. Thus, the accurate placement of devices in the system is important for obtaining the better voltage profile, lower cost of reactive power, and more loss reductions thereby higher annual savings of energy.

Analysis of the system after installation of D-STATCOM i.e., cost of energy loss, savings in cost of energy loss due to reduction in power losses, installation cost of D-STATCOM, and annual cost savings is given in Tables 4–7 respectively. For better understanding, real power loss after installation of

Table 5 Saving in cost of energy losses ($) after installation of D-STATCOM.

Time (h)	CPLS, proposed stability index (at 30th bus)				Voltage sensitivity index (at 25th bus)				FVSI, VSI (at 29th bus)			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
1	38,712	37,512	86,790	82,560	25,357	24,682	59,990	57,420	38,144	36,950	85,550	81,340
2	38,632	37,464	86,560	82,430	25,350	24,676	59,970	57,410	38,069	36,901	85,330	81,210
3	38,583	37,443	86,410	82,390	25,349	24,677	59,950	57,410	38,021	36,886	85,190	81,180
4	38,579	37,479	86,410	82,500	25,344	24,681	59,950	57,420	38,021	36,922	85,190	81,280
5	38,713	37,614	86,810	82,880	25,352	24,695	60,000	57,460	38,145	37,052	85,570	81,650
6	38,364	37,260	85,800	81,880	25,324	24,656	59,890	57,350	37,807	36,713	84,610	80,690
7	38,467	37,086	86,410	81,530	25,332	24,640	59,920	57,280	37,925	36,560	85,250	80,430
8	38,120	37,338	85,230	82,320	25,296	24,661	59,800	57,370	37,579	36,797	84,090	81,180
9	38,125	37,383	85,250	82,470	25,289	24,663	59,810	57,380	37,583	36,841	84,130	81,320
10	38,153	37,372	85,330	82,430	25,302	24,663	59,820	57,380	37,612	36,830	84,190	81,280
11	38,330	37,542	85,860	82,920	25,316	24,680	59,870	57,440	37,778	36,990	84,690	81,750
12	38,893	38,001	87,520	84,260	25,375	24,729	60,060	57,590	38,320	37,433	86,270	83,000
13	38,426	37,586	86,170	83,050	25,328	24,688	59,900	57,460	37,880	37,034	84,980	81,870
14	38,497	37,667	86,360	83,280	25,336	24,701	59,930	57,480	37,945	37,110	85,170	82,080
15	38,781	37,956	87,200	84,120	25,357	24,727	60,030	57,570	38,213	37,389	85,970	82,890
16	38,766	37,832	87,180	83,750	25,358	24,713	60,020	57,530	38,204	37,270	85,950	82,530
17	38,976	37,991	87,800	84,220	25,384	24,730	60,090	57,580	38,403	37,423	86,540	82,980
18	39,756	38,406	90,220	85,440	25,459	24,772	60,350	57,720	39,162	37,828	88,860	84,120
19	38,906	37,851	87,380	83,590	25,372	24,721	60,050	57,550	38,333	37,278	86,100	82,310
20	38,768	37,572	87,240	83,030	25,355	24,684	60,020	57,470	38,200	37,010	85,970	81,770
21	38,985	37,720	87,590	83,140	25,382	24,706	60,080	57,490	38,407	37,147	86,310	81,880
22	38,931	37,618	87,420	82,850	25,381	24,694	60,060	57,470	38,352	37,051	86,140	81,600
23	38,904	37,600	87,340	82,800	25,380	24,697	60,060	57,460	38,331	37,033	86,080	81,560
24	38,819	37,563	87,100	82,710	25,369	24,686	60,030	57,450	38,251	36,995	85,840	81,470

Table 6 Cost ($) of D-STATCOM.

Time (h)	CPLS, proposed stability index (at 30th bus)				Voltage sensitivity index (at 25th bus)				FVSI, VSI (at 29th bus)			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
1	5171.4	5038.8	7160.4	7027.8	2784.6	2784.6	4110.6	4110.6	5304	5171.4	7425.6	7293
2	5038.8	5038.8	7160.4	7027.8	2784.6	2784.6	4110.6	3978	5304	5171.4	7425.6	7293
3	5038.8	5038.8	7160.4	7027.8	2784.6	2784.6	4110.6	4110.6	5304	5171.4	7425.6	7293
4	5038.8	5038.8	7160.4	7027.8	2784.6	2784.6	4110.6	4110.6	5304	5171.4	7425.6	7293
5	5171.4	5038.8	7293	7027.8	2784.6	2784.6	4243.2	4110.6	5304	5171.4	7425.6	7293
6	5038.8	5038.8	7160.4	7027.8	2784.6	2784.6	4110.6	4110.6	5171.4	5171.4	7425.6	7160.4
7	5038.8	4906.2	7160.4	7027.8	2784.6	2784.6	4110.6	4110.6	5304	5171.4	7425.6	7160.4
8	5038.8	5038.8	7027.8	7027.8	2784.6	2784.6	4110.6	4110.6	5171.4	5171.4	7293	7293
9	5038.8	5038.8	6895.2	7027.8	2784.6	2784.6	4110.6	4110.6	5171.4	5171.4	7293	7293
10	5038.8	5038.8	7027.8	7027.8	2784.6	2784.6	4110.6	4110.6	5171.4	5171.4	7293	7293
11	5038.8	5038.8	7160.4	7027.8	2784.6	2784.6	4110.6	4110.6	5171.4	5171.4	7425.6	7293
12	5171.4	5038.8	7293	7160.4	2784.6	2784.6	4110.6	4110.6	5304	5304	7558.2	7293
13	5038.8	5038.8	7160.4	7160.4	2784.6	2784.6	4110.6	4110.6	5304	5171.4	7425.6	7293
14	5038.8	5038.8	7160.4	7160.4	2784.6	2784.6	4110.6	4110.6	5304	5171.4	7425.6	7425.6
15	5171.4	5038.8	7160.4	7160.4	2784.6	2784.6	4243.2	4110.6	5304	5304	7558.2	7425.6
16	5171.4	5038.8	7293	7160.4	2784.6	2784.6	4243.2	4110.6	5304	5171.4	7558.2	7425.6
17	5171.4	5038.8	7293	7160.4	2784.6	2784.6	4243.2	4110.6	5304	5304	7558.2	7425.6
18	5171.4	5038.8	7558.2	7293	2917.2	2784.6	4243.2	4243.2	5436.6	5304	7823.4	7558.2
19	5171.4	5038.8	7293	7160.4	2784.6	2784.6	4110.6	4110.6	5304	5304	7690.8	7293
20	5038.8	5038.8	7293	7027.8	2784.6	2784.6	4110.6	4110.6	5304	5171.4	7425.6	7293
21	5171.4	5038.8	7293	7027.8	2784.6	2784.6	4110.6	4110.6	5304	5171.4	7558.2	7293
22	5171.4	5038.8	7293	7027.8	2784.6	2784.6	4110.6	4110.6	5304	5171.4	7558.2	7293
23	5171.4	5038.8	7293	7027.8	2784.6	2784.6	4243.2	3978	5304	5171.4	7558.2	7293
24	5171.4	5038.8	7293	7027.8	2784.6	2784.6	4243.2	4110.6	5304	5171.4	7425.6	7293

D-STATCOM at 25th bus, 29th bus and 30th bus is presented in Table 8 for comparison. Comparison of minimum voltage, minimum voltage stability margin, Annual cost savings after installation of D-STATCOM at 25th bus, 29th bus and 30th bus is given in Figs. 23–25 respectively. Annual cost savings are higher with D-STACOM installed at 30th bus than D-

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

Table 7 Annual savings ($) after installation of D-STATCOM.

Time (h)	CPLS, proposed stability index (at 30th bus)				Voltage sensitivity index (at 25th bus)				FVSI, VSI (at 29th bus)			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
1	33,541	32,473	79,630	75,532	22,572	21,897	55,879	53,309	32,840	31,779	78,124	74,047
2	33,593	32,425	79,400	75,402	22,565	21,891	55,859	53,432	32,765	31,730	77,904	73,917
3	33,544	32,404	79,250	75,362	22,564	21,892	55,839	53,299	32,717	31,715	77,764	73,887
4	33,540	32,440	79,250	75,472	22,559	21,896	55,839	53,309	32,717	31,751	77,764	73,987
5	33,542	32,575	79,517	75,852	22,567	21,910	55,757	53,349	32,841	31,881	78,144	74,357
6	33,325	32,221	78,640	74,852	22,539	21,871	55,779	53,239	32,636	31,542	77,184	73,530
7	33,428	32,180	79,250	74,502	22,547	21,855	55,809	53,169	32,621	31,389	77,824	73,270
8	33,081	32,299	78,202	75,292	22,511	21,876	55,689	53,259	32,408	31,626	76,797	73,887
9	33,086	32,344	78,355	75,442	22,504	21,878	55,699	53,269	32,412	31,670	76,837	74,027
10	33,114	32,333	78,302	75,402	22,517	21,878	55,709	53,269	32,441	31,659	76,897	73,987
11	33,291	32,503	78,700	75,892	22,531	21,895	55,759	53,329	32,607	31,819	77,264	74,457
12	33,722	32,962	80,227	77,100	22,590	21,944	55,949	53,479	33,016	32,129	78,712	75,707
13	33,387	32,547	79,010	75,890	22,543	21,903	55,789	53,349	32,576	31,863	77,554	74,577
14	33,458	32,628	79,200	76,120	22,551	21,916	55,819	53,369	32,641	31,939	77,744	74,654
15	33,610	32,917	80,040	76,960	22,572	21,942	55,787	53,459	32,909	32,085	78,412	75,464
16	33,595	32,793	79,887	76,590	22,573	21,928	55,777	53,419	32,900	32,099	78,392	75,104
17	33,805	32,952	80,507	77,060	22,599	21,945	55,847	53,469	33,099	32,119	78,982	75,554
18	34,585	33,367	82,662	78,147	22,542	21,987	56,107	53,477	33,725	32,524	81,037	76,562
19	33,735	32,812	80,087	76,430	22,587	21,936	55,939	53,439	33,029	31,974	78,409	75,017
20	33,729	32,533	79,947	76,002	22,570	21,899	55,909	53,359	32,896	31,839	78,544	74,477
21	33,814	32,681	80,297	76,112	22,597	21,921	55,969	53,379	33,103	31,976	78,752	74,587
22	33,760	32,579	80,127	75,822	22,596	21,909	55,949	53,359	33,048	31,880	78,582	74,307
23	33,733	32,561	80,047	75,772	22,595	21,912	55,817	53,482	33,027	31,862	78,522	74,267
24	33,648	32,524	79,807	75,682	22,584	21,901	55,787	53,339	32,947	31,824	78,414	74,177

Table 8 Comparison of real power losses after installation of D-STATCOM.

Time (h)	CPLS, proposed stability index (at 30th bus)				Voltage sensitivity index (at 25th bus)				FVSI, VSI (at 29th bus)			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
1	130.78	127.07	339.51	323.95	156.19	151.48	390.5	371.78	131.86	128.14	341.87	326.28
2	130.99	127.39	340.44	325.35	156.26	151.72	391.04	372.95	132.06	128.46	342.78	327.66
3	131.12	127.6	341.04	326.22	156.3	151.89	391.38	373.75	132.19	128.66	343.36	328.52
4	131.11	127.57	340.98	326.09	156.29	151.92	391.33	373.8	132.17	128.63	343.3	328.4
5	130.74	126.99	339.32	323.57	156.16	151.57	390.34	371.93	131.82	128.06	341.69	325.92
6	131.69	128.52	343.65	330.2	156.5	152.5	392.95	376.87	132.75	129.56	345.91	332.45
7	134.12	132.39	354.51	347.12	159.11	156.07	404.9	393.26	135.15	133.39	356.71	349.22
8	132.99	131.7	349.67	344.11	157.39	155.82	398.06	391.58	134.02	132.73	351.84	346.28
9	132.83	131.54	348.97	343.36	157.25	155.74	397.37	391.09	133.86	132.57	351.1	345.54
10	132.89	131.58	349.2	343.54	157.34	155.76	397.74	391.19	133.92	132.61	351.37	345.72
11	132.44	130.99	347.12	340.92	157.2	155.46	396.57	389.4	133.49	132.04	349.35	343.15
12	131.33	129.47	342.02	334.12	157.05	154.72	394.28	384.86	132.42	130.55	344.4	336.52
13	132.37	130.83	346.73	340.16	157.29	155.37	396.7	388.86	133.41	131.88	348.99	342.41
14	132.16	130.58	345.81	339.05	157.2	155.25	396.1	388.12	133.21	131.64	348.08	341.32
15	131.41	129.63	342.41	334.85	156.95	154.8	394.11	385.36	132.49	130.71	344.75	337.2
16	131.8	130	344.12	336.47	157.31	154.96	395.79	386.35	132.87	131.07	346.46	338.79
17	131.42	129.47	342.37	334.11	157.28	154.7	395.09	384.79	132.51	130.55	344.77	336.48
18	130.64	128.07	338.64	327.88	157.84	154.01	395.48	380.61	131.77	129.17	341.23	330.38
19	130.22	126.14	336.95	319.92	155.97	151.12	388.94	369.47	131.31	127.23	339.39	322.36
20	127.42	123.36	329.29	312.41	152.94	147.88	381.06	361.04	128.5	124.43	331.7	314.8
21	130.09	125.97	336.36	319.25	155.97	150.73	388.7	368.05	131.19	127.06	338.8	321.65
22	130.25	126.24	337.09	320.4	156.03	150.83	389.14	368.69	131.35	127.32	339.51	322.77
23	130.32	126.35	337.4	320.86	156.05	150.9	389.31	369.07	131.41	127.43	339.81	323.22
24	130.52	126.65	338.29	322.17	156.11	151.15	389.81	370.23	131.6	127.73	340.69	324.52

STATCOM placed at 25th and 29th bus. This is due to the higher reduction in power losses with D-STATCOM placed optimally at 30th bus compared to other buses. Total real power losses in case A for first hour are 130.78 kW after placement of D-STATCOM at 30th bus, 156.19 kW after placement of D-STATCOM at 25th bus and 131.86 kW after placement

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

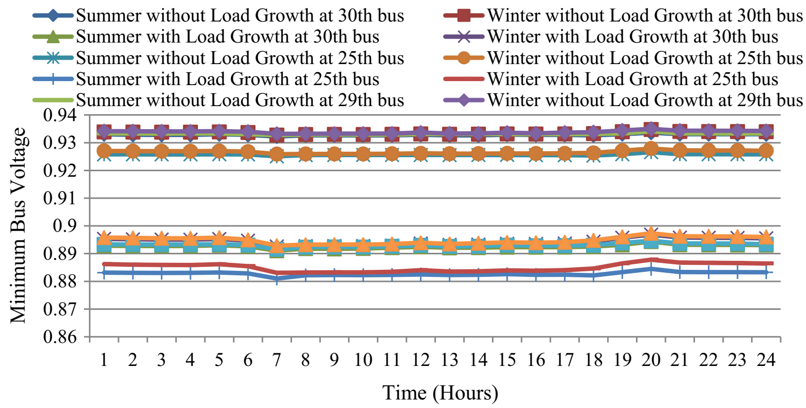

Figure 23 Comparison of minimum voltage after installation of D-STATCOM.

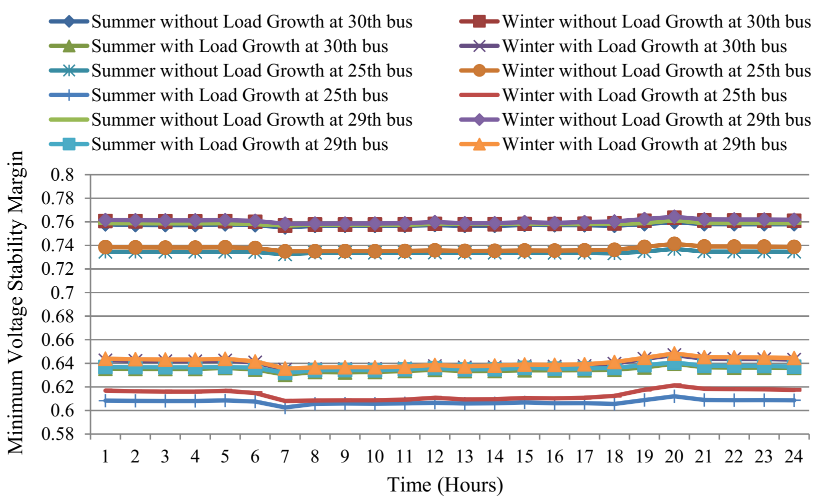

Figure 24 Comparison of voltage stability margin after installation of D-STATCOM.

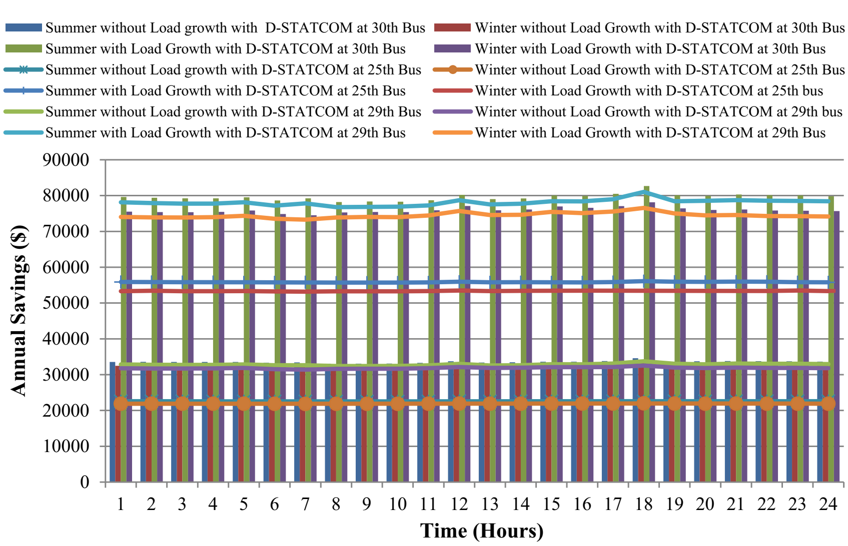

Figure 25 Annual cost savings after installation of D-STATCOM in mesh distribution system.

of D-STATCOM at 29th bus as observed from Table 8. Similarly comparative results for all other cases for each our can be seen easily from Table 8. It is concluded that the location of the D-STATCOM is better obtained with CPLS and the proposed stability index compared to the other sensitivity indices.

7. Conclusions

In this paper, optimal D-STATCOM placement and size are obtained based on sensitivity approaches for a mesh distribution system. A new stability index is proposed for optimal placement of D-STATCOM for mesh distribution system. Based on the analysis carried out, the following conclusions are made:

- The placement of D-STATCOM based on the sensitivity method CPLS and the proposed SI is better compared to other sensitivity methods as the sizes of D-STATCOM are lower for KVAR support and thereby the cost of D-STATCOM/KVAR is also lower.
- Average summer load is slightly higher than winter load, thereby D-STACOM rating is also slightly higher in summer than in winter season.
- With the D-STATCOM, there is significant improvement in voltage profile, enhanced voltage stability margin, reduction in power losses and cost of energy losses and thereby annual energy savings are higher.
- Power losses increase with load growth accordingly, and the required D-STATCOM KVAR support also increases to meet reactive power requirements of load growth. Annual energy savings obtained due to energy loss reduction are higher with load growth after installation of D-STATCOM.

The proposed sensitivity method and CPLS give better location compared to the other sensitivity indices as voltage profile, losses, enhanced voltage stability margins and lower cost of reactive support/KVAR are better. The annual savings obtained with D-STATCOM without and with load growth are observed higher when the device is placed at 30th bus. Hence, this study can help the system operator to plan the better distribution system with optimal reactive power planning.

Acknowledgments

The authors gratefully acknowledge MHRD, Govt. of India for providing research facilities to the work reported in this paper.

References

[1] Ng HN, Salama MMA, Chikhani AY. Classification of capacitor allocation techniques. IEEE Trans Power Delivery 2000;15(1):387–92.
[2] Ramsay SM, Cronin PE, Nelson RJ, Bian J, Menendez FE. Using distribution static compensators (DSTATCOMs) to extend the capability of voltage-limited distribution feeders. In: 40th Annual Conference Rural Electric Power Conference. http://dx.doi.org/10.1109/REPCON.1996.495235. April, A4/18–A4/24.
[3] Hosseini M, Shayanfar HA. Regular paper modeling of series and shunt distribution FACTS devices in distribution systems load flow. J Electr Syst 2008;4(4):1–22.
[4] Hussain SMS, Visali N. Identification of weak buses using voltage stability indicator and its voltage profile improvement by using DSTATCOM in radial distribution systems. IOSR J Electr Electron Eng 2012;2(4):17–23.
[5] Taher SA, Afsari SA. Optimal location and sizing of DSTATCOM in distribution systems by immune algorithm. Electr Power Energy Syst 2014;60:34–44.
[6] Devi S, Geethanjali M. Optimal location and sizing determination of distributed generation and DSTATCOM using particle swarm optimization algorithm. Electr Power Energy Syst 2014;62:562–70.
[7] Hussain SMS, Subbaramiah M. An analytical approach for optimal location of D-STATCOM in radial distribution system. In: IEEE international conference on energy efficient technologies for sustainability (ICEETS). p. 1365–9.
[8] Farhoodnea M, Mohamed A, Shareef H, Zayandehroodi H. Optimum D-STATCOM placement using firefly algorithm for power quality enhancement. In: IEEE 7th international power engineering and optimization conference (PEOCO). p. 98–102, June.
[9] Tolabi HB, Ali MH, Rizwan M. Simultaneous reconfiguration, optimal placement of D-STATCOM, and photovoltaic array in a distribution system based on fuzzy-ACO approach. IEEE Trans Sustain Energy 2015;6(1):210–8.
[10] Yuvaraj T, Ravi K, Devabalaji KR. DSTATCOM allocation in distribution networks considering load variations using bat algorithm. Ain Shams Eng J 2015. http://dx.doi.org/10.1016/j.asej.2015.08.006, Elsevier, [in press].
[11] Devabalaji KR, Ravi K. Optimal size and siting of multiple DG and DSTATCOM in radial distribution system using bacterial foraging optimization algorithm. Ain Shams Eng J 2015. http://dx.doi.org/10.1016/j.asej.2015.07.002 [in press].
[12] Sanam J, Ganguly S, Panda AK. Placement of DSTATCOM in radial distribution systems for the compensation of reactive power, Smart Grid Technologies - Asia (ISGT ASIA). IEEE Innovative, Bangkok 2015;2015:1–6. http://dx.doi.org/10.1109/ISGT-Asia.2015.7387036.
[13] Yuvaraj T, Devabalaji KR, Ravi K. Optimal placement and sizing of DSTATCOM using harmony search algorithm. Energy Procedia 2015;79:759–65.
[14] Kanwar N, Gupta N, Niazi KR, Swarnkar A. Improved cat swarm optimization for simultaneous allocation of DSTATCOM and DGs in distribution systems. J Renew Energy 2015:10. http://dx.doi.org/10.1155/2015/189080. Article ID 189080.
[15] Gupta AR, Kumar A. Energy savings using D-STATCOM placement in radial distribution system. Procedia Comput Sci 2015;70:558–64.
[16] Deepmala, Kumar A. Impact of load models on distribution system performance and impact of D-STATCOM. In: 6th IEEE power india international conference (PIICON), Delhi. p. 1–6.
[17] Haque MH. Efficient load flow method for distribution systems with radial or meshed configuration. IEE Proc-Gener Transm Distrb 1996;143(1):33–8.
[18] Teng JH. A direct approach for distribution system load flow solutions. IEEE Trans Power Delivery 2003;18(3):882–7.
[19] Sharma AK, Murty VVSN. Analysis of mesh distribution systems considering load models and load growth impact with loops on system performance. J Inst Eng (India): Ser B 2014;95(4):295–318.
[20] Parizad A, Khazali A, Kalantar M. Optimal placement of distributed generation with sensitivity factors considering voltage stability and losses indices. In: Proceedings of IEEE 18th Iranian conference on electrical engineering ICEE 2010. p. 1–8, May.
[21] Murthy VVSN, Kumar Ashwani. Comparison of optimal DG allocation methods in radial distribution systems based on sensitivity approaches. Int J Electr Power Energy Syst 2013;53:450–67.
[22] Chakrabarti A, Kothari DP, Mukhopadhyay AK, De Abhinandan. An introduction to reactive power control and voltage stability in power transmission. PHI Learning Private Limited; 2000.
[23] Murty VVSN, Kumar Ashwani. Optimal placement of DG in radial distribution systems based on new voltage stability index under load growth. Int J Electr Power Energy Syst 2015;69:246–56.

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009

[24] Murty VVSN, Kumar Ashwani. Mesh distribution system analysis in presence of distributed generation with time varying load model. Int J Electr Power Energy Syst 2014;62:836–54.
[25] Qian K, Zhou C, Allan M, Yuan Y. Effect of load models on assessment of energy losses in distributed generation planning. Int J Electr Power Energy Syst 2011;33(6):1243–50.
[26] The MATLAB by Mathworks Corporation. MATLAB version 2009;7:8.
[27] A descriptive bulletin on voltage support for transmission systems S&C PureWave DSTATCOM, available on http://www.sandc.com/.
[28] Gozel T, Eminoglu U, Hocaoglu MH. A tool for voltage stability and optimization (VS&OP) in radial distribution systems using matlab graphical user interface (GUI). Simul Model Pract Theory 2008;16(5):505–18.

Atma Ram Gupta received his B.Tech in Electrical Engineering from C V Raman College of Engineering, Bhubaneshwar, and M. Tech from National Institute of Technology, Durgapur, in 2009 and 2012 respectively. He is presently working as an Assistant Professor in Electrical Engineering Department at National Institute of Technology, Kurukshetra, Haryana. He is currently working on his thesis for Ph.D degree in Electrical Engineering in NIT Kurukshetra from 2013. His research interest includes Power Systems, D-FACTs placement in distribution system, Power Systems restructuring, incorporation of renewable energy sources in distribution system, Reactive power management and distribution pricing. He is a member of IEEE.

Ashwani Kumar is presently working as Professor in the Department of Electrical Engineering at NIT-Kurukshetra, Haryana. He received his B.Tech in Electrical Engineering from Pant Nagar University in 1988 and Master degree in Power Systems from Panjab University, Chandigarh, in 1994 in honors. He received his Ph.D. from Indian Institute of Technology-Kanpur in 2003. He did Post Doctoral from Tennessee Technological University, USA. He has started collaboration with academic Institutions/R&D Labs including IIT Kanpur and Delft Uni. Netherlands for the project work in the area of Smart Grids. He has executed three research projects sponsored by different funding agencies including DST and AICTE. He has also carried out few consultancies assignments for power companies. His research interest includes Power Systems, Power Systems restructuring, Transfer capability assessment, congestion management, Demand side management, distributed generation integration, Reactive power management and Ancillary services, Transmission and distribution pricing. He has more than 100 publications in the journals of repute including IEEE Trans. on Power Systems, IET-GTD, Elsevier, Taylor and Francis, Springer, Berkeley, Emerald, JES, and IEI series B. He has guided 5 Ph.D and more than 35 M.Tech research theses. Four of his research students have been awarded with prestigious POSOCO Power System Award (PPSA) for best Thesis in the year 2012, 2013, and 2014 on all India level.

Please cite this article in press as: Gupta AR, Kumar A. Optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth. Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.05.009