Application of Particle Swarm Optimization and Its Variant for Optimum Load Shedding

L. D. Arya, M. Shrivastava, and S. C. Choube

Abstract—**This paper describes a methodology for obtaining minimum load-shed at selected buses from voltage stability margin viewpoint. The buses for load-shed have been selected based on line voltage stability index and its sensitivities at operating point. Computational algorithms for minimum load-shed have been developed using conventional particle swarm optimization (PSO) and coordinated aggregation based particle swarm optimization (CAPSO) one of its variant. Using these two algorithms load-shed results for two sample test systems have been obtained and compared.**

Index Terms—**Voltage stability, load-shed, line voltage stability index, optimization, PSO.**

I. INTRODUCTION

LOAD-SHED is an action required once the system enters in a state of non-correctable emergency. Disturbances caused by contingent conditions may move the power network close to voltage instability. Well planned preventive actions are required for this purpose. Load shedding is initialized as last line of defense. In many practical situations load shedding is initialized by the under voltage relays [1], [2]. It has been established that under voltage criterion has poor discriminative ability and in fact proper discrimination for load-shed may be obtained from voltage stability margin view point [3]. Load-shed criterion may be based on some proximity indicator whose magnitude indirectly reflects the stability margin and provides information for initialization of load shedding. Under such situation the magnitude of the indicator may be monitored during normal operating condition and when it falls below a threshold value alarm should be actuated. If the indicator continues to decline and reaches to another lower value load-shed is to be initiated. Such situation may arise due to (i) sudden loss of generation/increase in load which may result in decrease in frequency (ii) outage of one or more transmission line thus reducing network loadability and may cause load bus limit violations and (iii) Overloading of transmission line. In view of this load shedding may be adopted based on (i) under frequency consideration [4], [5], (ii) Over load alleviation of transmission lines [6] and (iii) voltage limit violation/voltage stability considerations [9].

Voltage instability may be avoided by taking emergency measures such as (i) decreasing voltage set point (ii) blocking on load tap changers (iii) appropriate load shedding at selected load buses. Limited research work has been done on load shedding to avoid risk of voltage collapse. Berg and Sharaf [9] developed a load shedding strategy based on nonlinear programming which maximizes reactive power security margin. El-Sadek *et al*. [10] developed a methodology for optimum load-shed as a emergency mean to avoid voltage collapse using L-indicator. Successive load flow runs are required to accomplish proposed technique. Bijwe *et al*. [11] developed an anticipatory load shedding technique using LP formulation. Jung *et al*. [12] described an application of multi agent system for assessment of power system vulnerability and perform self healing and corrective and preventive control action. A convergence criterion constrained load shedding agent is trained for optimal load shedding. Echavarren *et al*. [13] presented a LP based optimization algorithm for load-shed to improve load margin considering first order load margin sensitivities. A method for optimal load shedding considering generation deficiency in a power system has been developed by Hazarika and Sinha [14]. Chattopadhyay and Chakraborti [15] presented a preventive control model to prevent voltage instability accounting dynamics of load-shed. Amraee *et al*. [16] developed an optimal load shedding algorithm which is based on the concept of the static voltage stability margin and its sensitivity at the maximum loading point.

This paper describes an optimal load-shed algorithm which consists of two parts one of it identifies buses for load-shed and the other determines the optimum load-shed at these buses using PSO and coordinated aggregation based particle swarm optimization (CAPSO). Sensitivities of line voltage stability index [17] have been used to select the buses for load-shed. Optimum load shedding at these buses have been obtained so as to satisfy voltage stability constraints.

II. LINE VOLTAGE STABILITY INDEX AND SENSITIVITY CALCULATIONS

A line voltage stability index has been derived in [17] given as follows

$$L_i = A\, v\, Cos(\delta - \alpha) \qquad (1)$$

At collapse point the magnitude of the line voltage stability index approaches to 0.5. In (1) the symbols are defined as follows

A ‘A’ constant of the transmission line
α is the phase angle of ‘A’ constant
k, m are the buses to which i th line is connected.
V_k, V_m are the bus voltage magnitudes
m th end is receiving real power.
$v = V_m / V_k$
$\delta = \delta_k - \delta_m$ is phase angle across transmission line.

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L. D. Arya and S. C. Choube are with Electrical Engineering Department, S.G.S.I.T.S Indore, India. (e-mails: ldarya@rediffmail.com, scchoube@yahoo.co.in).

M. Shrivastava is with Electrical Eng. Dept., Ujjain Engineering College Ujjain, India. (e-mail: mrid_shrivastava@yahoo.com).

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It has been established that for system to be stable L_i for lines in a power network must be greater than 0.5. From no load to voltage collapse point, the value of line voltage stability index (L_i) varies from $A\,Cos\,\alpha$ (nearly one) to 0.5. At maximum loadability point one of the lines goes critical. Sensitivities of such transmission line with respect to real and reactive power injections are used for selection of buses for load shed. Line voltage stability index for such line is monitored [21]. The sensitivities are defined as

$$\frac{\partial L_i}{\partial Q_r} = b_{i,r} \tag{2}$$

$$\frac{\partial L_i}{\partial P_r} = a_{i,r} \tag{3}$$

a_{ir} and b_{ir} are sensitivity coefficients of line voltage stability index for critical line 'i' with respect to real and reactive power injection changes at rth bus respectively. Differentiating (1) with respect to real and reactive power injections, expressions for a_{ir}, b_{ir} are obtained as follows

$$\begin{aligned} a_{i,r} &= \frac{A_i}{V_k^{\,2}}\left(V_k.\frac{\partial V_m}{\partial P_r} - V_m.\frac{\partial V_k}{\partial P_r}\right)Cos(\delta-\alpha) \\ &\quad - A_i\frac{V_m}{V_k}Sin(\delta-\alpha)\left(\frac{\partial\delta_k}{\partial P_r} - \frac{\partial\delta_m}{\partial P_r}\right) \end{aligned} \tag{4}$$

$$\begin{aligned} b_{i,r} &= \frac{A_i}{V_k^{\,2}}\left(V_k.\frac{\partial V_m}{\partial Q_r} - V_m.\frac{\partial V_k}{\partial Q_r}\right)Cos(\delta-\alpha) \\ &\quad - A_i\frac{V_m}{V_k}Sin(\delta-\alpha)\left(\frac{\partial\delta_k}{\partial Q_r} - \frac{\partial\delta_m}{\partial Q_r}\right) \end{aligned} \tag{5}$$

In (4) and (5), the partial derivatives $\partial V_m/\partial P_r$, $\partial\delta_k/\partial P_r$, $\partial\delta_m/\partial P_r$ $\partial V_m/\partial Q_r$, $\partial V_k/\partial Q_r$, $\partial\delta_k/\partial Q_r$, $\partial\delta_m/\partial Q_r$ are directly obtained at the end of N-R load flow solution as elements of inverted matrix of load flow Jacobian [22].

Total change in line voltage stability index of critical line may be written using sensitivities a_{ir} and b_{ir} as

$$\Delta L_i = a_{i\,r}.\Delta P_r + b_{i\,r}.\Delta Q_r \tag{6}$$

Assuming constant power factor load

$$\Delta Q_r = \beta_r\,.\Delta P_r \tag{7}$$

where β_r is given as $\beta_r = \tan(\Phi_r)$, Φ_r is the power factor angle of rth bus.

Putting (7) in (6) following relation for total change in index of critical line is obtained as $\Delta Li = SL_{i\,r}\ \Delta P$ where $SL_{i\,r}$ is identified as $SL_{ir} = a_{i\,r} + \beta_r b_{i\,r}$.

III. PROBLEM FORMULATION FOR OPTIMAL LOAD–SHED AT SELECTED BUSES

Buses are selected for load-shed according to the sensitivity of line voltage stability index of critical line with respect to load-shed at the buses. The objective function is defined as

$$J = \sum_{i\in NLS} LS_i \tag{8}$$

NLS is the set of buses selected for load-shed. Hence objective function is minimization of total real power load-shed. Objective function is minimized subject to following constraints

(i) $0 \le \mathrm{LS_i} \le \mathrm{LS_{i,\,max}} \qquad \mathrm{i} \ge \mathrm{NLS}$ (9)

LS_i is the amount of real power load-shed and $LS_{i,\max}$ denotes maximum permissible load-shed at ith bus. In fact permissible load-shed is a fraction of total load at selected bus. It may be say 80% of the total load and rest 20% may be a load which is required in emergency condition. This depends on utility policy.

(ii) After load-shed voltages of all load buses should be within limits

$$V_{i,\ \min} \ge Vi \ge V_{i,\ \max} \qquad i = NG+1 \ldots NB \tag{10}$$

(iii) Stability constraints: All line voltage stability indices should be greater than threshold values

$$Li \ge L_{i,\,Th} \qquad i = 1,2,\ldots NL \tag{11}$$

IV. SOLUTION METHODOLOGY USING PARTICLE SWARM OPTIMIZATION (PSO)

The PSO algorithm is implemented in following steps which is a population based heuristic search algorithm [18].

Step-1: Select 'M' feasible solution by generating random digits from uniform distribution $[0,\ LS_{i,\ \max}]$ i.e.

$$\mathrm{X_i(0)=[LS_{i1}^{(0)},\ LS_{i2}^{(0)}, \ldots\ LS_{iNLS}^{(0)}]^T,\ \ i = 1,2,\ldots\ldots M} \tag{12}$$

These solutions in terms of load-shed satisfy the constraints (9), (10) and (11). Incremental power flow equations are used to check the feasibility of the solutions. Each of such solutions is termed as an agent or particle and these 'M' solutions are known as swarm.

Step-2: Calculate for each particle obtained in previous step, objective function given by relation (5). Label the particle as $G_{best}^{(0)}$ which gives minimum value of objective function. Also label each particle as its best as $P_{best,i}^{(0)}$ and store corresponding values of objective function.

Step-3: Generate initial velocity for each particle as low random number as follows

$$\rho_{\mathrm{i}}^{(0)}=[\rho_{\mathrm{i1}}^{(0)},\ \rho_{\ \mathrm{i2}}^{(0)},\ \rho_{\ \mathrm{i3}}^{(0)}, \ldots \rho_{\mathrm{i,NLS}}^{(0)}]^{\mathrm{T}}\ \ \mathrm{i=1,2,\ldots M} \tag{13}$$

Each component of $\rho_i^{(0)}$ may be generated from uniform distribution e.g. between [-0.01, +0.01].

Step-4: Set iterations count $k = 1$.

Step-5: Update the velocity of each particle using following relation

$$\begin{aligned} \rho_i^{(k)} &= W.\,\rho_i^{(k\text{-}1)} + c_1.r_1(P_{best,i}^{(k\text{-}1)} - X_i^{(k\text{-}1)}) + \\ &\qquad c_2.r_2\ (G_{best}^{(k\text{-}1)} - X_i^{(k\text{-}1)}) \end{aligned} \tag{14}$$

where r_1, r_2 are random digits between [0,1], c_1, c_2 are acceleration constants selected in the range [1,2], W is the inertia weight.

Step-6: Update the position of each particle and obtain modified solution as follows

$$X_i^{(k)} = X_i^{(k\text{-}1)} + \rho_i^{(k)} \tag{15}$$

The resulting position of an individual i.e. $X_i^{(k)}$ may not satisfy the inequality constraints. In such situation the particle is fly-back to previous position [19].

To explore local as well as global feasible space inertia weight is varied iteration wise as $W = W_{\max} - (W_{\max} - W_{\min})\times N/N_{\max}$ where $N_{\max}$ is maximum number of iterations specified N denotes current iteration. $W_{\max}$, $W_{\min}$ denote maximum and minimum values of inertia weights.

Step-7: Particles best $P_{best,i}$ and group best G_{best} are updated.

$$\mathrm{P_{best,i}}^{(\mathrm{k})} = \begin{cases} \mathrm{X_i}^{(\mathrm{k})} & \text{If } \mathrm{J(X_i^{(k)}) < J(P_{best,i}{}^{(k-1)})} \\ \mathrm{P_{best,i}}^{(\mathrm{k-1})} & \text{If } \mathrm{J(X_i^{(k)}) \geq J(P_{best,i}{}^{(k-1)})} \end{cases}$$

where $J(X_i^{(k)})$ is the magnitude of objective function. $J(P_{best,i}{}^{(k\text{-}1)})$ is the value of objective function for previous best particle 'i'. Very best $P_{best,i}{}^{(k)}$ set as group best position i.e. $G_{best,}{}^{(k)}$.

Step-8: The PSO algorithm is terminated after a maximum number of iterations have been executed or no improvement is found in the objective function for a specified number of iterations.

V. OPTIMAL SOLUTION USING COORDINATED AGGREGATION BASED PARTICLE SWARM OPTIMISATION (CAPSO)

CAPSO is an improved version of conventional PSO [19]. Each particle moves considering only the positions of particles with better achievements than its own, with the exception of the best particle, which moves randomly. The coordinated aggregation can be considered as a type of active aggregation where particles are attracted only by places with the most food. Hence this method differs from the one described in previous section only in updating the velocity of each particle (step-5). Velocity is updated using following relation

$$\rho_i^{(k)} = W \times \rho_i^{(k-1)} + \sum_j r_j W_{ij}^{(k-1)} [X_j^{(k-1)} - X_i^{(k-1)}] \qquad (16)$$

where r_j, denotes random digits between [0,1], W_{ij} is known as achievement factor, which is the ratio of differences between the achievement (objective function) of particle-I and better achievements by particles-j to the sum of all these differences. Expression for W_{ij} is given as follows

$$W_{ij}^{(k-1)} = \frac{J_j^{(k-1)} - J_i^{(k-1)}}{\sum_l [J_l^{(k-1)} - J_i^{(k-1)}]} \qquad (17)$$

where $J_j^{(k\text{-}1)}$, $J_i^{(k\text{-}1)}$ are the values of objective function at positions $X_j^{(k\text{-}1)}$ and $X_i^{(k\text{-}1)}$ respectively.

l Є T, 'T' represents the set of particles-j with better achievements in terms of objective function.

Relation (16) is used to update the velocities of all particles except the best particle in swarm. The best particle in swarm is updated using a random coordinator calculated between its position and the position of a randomly chosen particle in a swarm as follows

$$\rho_p^{(k)} = W.\, \rho_{p(k\text{-}1)} + r[\, X_l^{(k\text{-}1)} - X_p^{(k\text{-}1)}] \qquad (18)$$

$X_l^{(k\text{-}1)}$ is a randomly selected particle. $X_p^{(k\text{-}1)}$ is the best particle in swarm, r is random digit between [0,1]. The updating of best particle of group behaves in a crazy way and helps the swarm to escape from local minima.

Remaining steps are same as in standard PSO explained in previous section. CAPSO has better convergence characteristics and requires fewer random parameters to start than other techniques.

VI. RESULTS AND DISCUSSIONS

The developed algorithm for load-shed has been implemented on 14 and 25-bus standard test systems [22].

TABLE I

INITIAL SWARM OF FIVE PARTICLES FOR 14-BUS SYSTEM

SN	Amount of load-shed in pu at selected bus			Total Load-shed
	Bus No. 4	Bus No.6	Bus No.9	
1	0.0195	0.7906	0.5344	1.3441
2	0.0215	0.6540	0.5337	1.2092
3	0.0212	0.6772	0.5407	1.2390
4	0.0218	0.7016	0.5498	1.2731
5	0.0219	0.7376	0.5193	1.2787

TABLE II

OPTIMAL LOAD-SHED AT DIFFERENT BUSES FOR 14-BUS SYSTEM

Method	Amount of load-shed in pu at selected bus			Total Load-shed **(pu)**
	Bus No.4	Bus No.6	Bus No.9	
PSO	0.0227	0.4283	0.5632	1.0143
CAPSO	0.0229	0.4414	0.5616	1.0259

Threshold value of all line voltage stability indices are selected as 0.65. Limits on load bus voltage have been between 0.9 and 1.05 pu. Further permissible load-shed at each bus is assumed as 80% of the total load at that bus. An initial swarm of five particles was selected. $W_{\max}$ and $W_{\min}$ were selected as 1.0 and 0.1 respectively. c_1 and c_2 were selected as 1.0 each. Other combinations of $W_{\max}$, $W_{\min}$ and c_1, c_2 were tried. The convergence obtained with this combination was found best in terms of CPU time. Maximum number of iterations $N_{\max}$ is 100.

The 14-bus system has in all 20 lines. Load on the system is 9.536 pu and 3.281 pu real and reactive respectively. Voltage stability margin in terms of real and reactive power distance is 0.4768 pu and 0.1640 pu respectively. The margin is inadequate. Line no. 9 is observed as critical line whose line voltage stability index is 0.5994.

Sensitivities of line voltage stability index of critical lines with respect to load-shed at the buses are evaluated. The buses having highest sensitivity are 4, 6 and 9 have been selected for load shed. An initial swarm of five particles is shown in Table I. Each particle represents a feasible solution. Same Table provides value of objective function. Particle number 2 is $G_{best}{}^{(0)}$. Using PSO, solution converged in 10 iterations. Total CPU time required 8 sec. on HCL 486 machine. Optimum solution with same initial swarm was obtained using CAPSO. Number of iterations required for convergence are 5. Total CPU time required on the same machine is 4 sec. Table II shows optimal load-shed obtained at selected bus along with value of objective function by both the methods. Fig. 1 shows voltage profile before load-shed and after load-shed. It is observed that all load bus voltages are within limits. Before load-shed load bus voltages 4, 5, 7, 9, 10, 11, 12, 13 and 14 were below 0.9. Hence bus voltages with violations are brought within limits. Fig. 2 shows the line voltage stability indices for all the lines before and after load-shed. For all the lines, line voltage stability indices are having greater magnitude than 0.65. After load-shed the stability margin from current operating point is 3.591 pu and 1.235 pu real and reactive power respectively. Fig. 3 shows plot of objective function $J(G_{best}{}^{k})$ with increasing number of iterations as obtained using PSO and CAPSO method. It is observed that CAPSO has better convergence characteristic in terms of number of iterations and CPU time required.

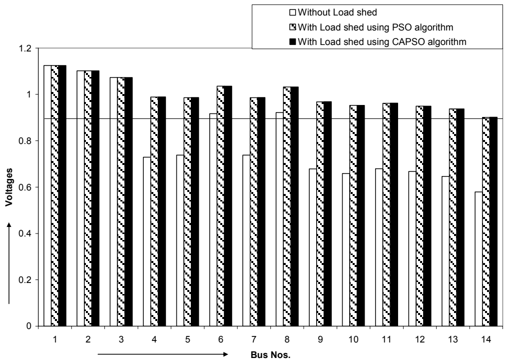

Fig. 1. Represents bus voltages before and after load shedding for 14-bus system.

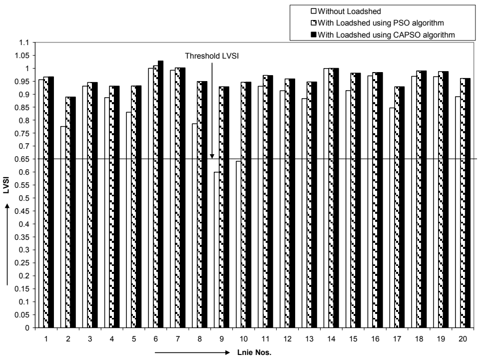

Fig. 2. Represents line voltage stability index before and after load-shed for 14-bus system.

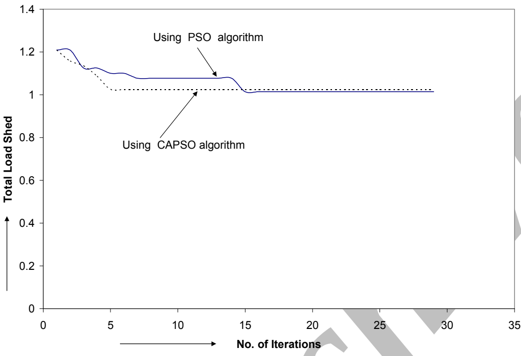

Fig. 3. Convergence of total load-shed with respect to no. of iterations using PSO and CAPSO algorithm for 14-bus system.

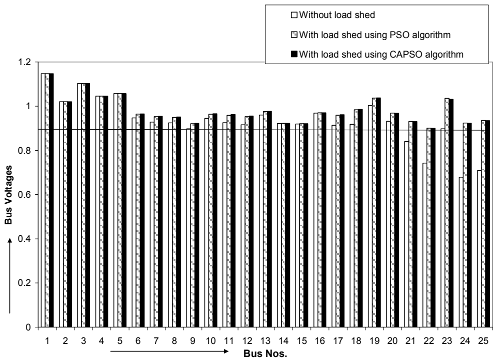

Fig. 4. Represents bus voltages before and after load shedding for 25-bus system.

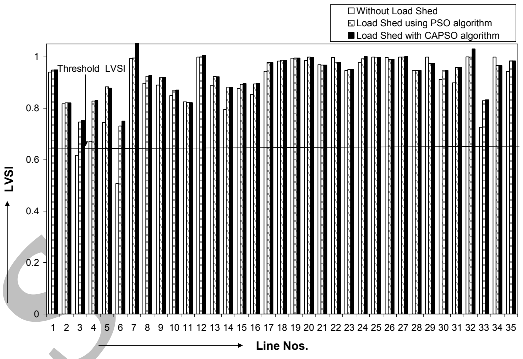

Fig. 5. Represents line voltage stability index before and after load-shed for 25-bus system.

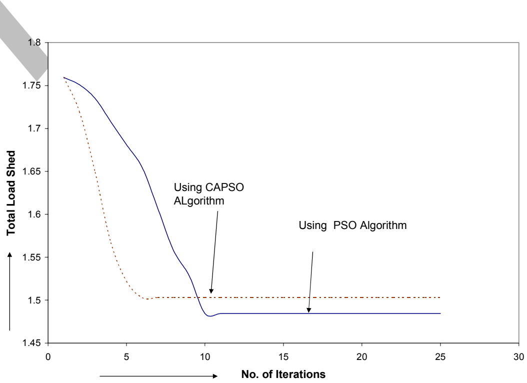

Fig. 6. Convergence of total load-shed with respect to no. of iterations using PSO and CAPSO algorithm for 25-bus system.

Similar results have been obtained for 25-bus system. This system has in all 5 generators and 35 lines. Line no. 6 is observed as critical line whose line voltage stability index is 0.5071 with total real load of 13.03 pu and reactive load of 3.925 pu. Voltage stability margin is 0.6515 pu real and 0.1962 pu reactive.

Sensitivities of line voltage stability index of critical lines with respect to load-shed at the buses are evaluated and buses having highest sensitivity are selected for load-shed. Selected buses for load-shed are 11, 12, 18, 19, 23, and 24 with sensitivities 15.52, 7.76, 5.173, 5.173, 5.173, and 5.173, respectively. An initial swarm of five particles with the value of objective function is shown in Table III. Each particle represents a feasible solution. Particle number 5 is $G_{best}^{(0)}$. Using PSO solution converged in 12 iterations. Total CPU time required 9 sec. Optimum solution with CAPSO algorithm requires 5 iterations for convergence. Total CPU time required on the same machine is 5 sec.

Table IV shows optimal load-shed obtained at selected bus along with value of objective function by both the methods. Fig. 4 shows voltage profile before load-shed and after load shed. Voltages of bus nos. 9, 21, 22, 23, 24, 25 were below 0.9 before load-shed. It is observed that after load-shed all bus voltages are within limits. Fig. 5 shows the line voltage stability indices for all the lines before and after load-shed and indices for all lines greater magnitude than threshold value (0.65). After load-shed the stability margin from current operating point is 2.5315 pu and 0.7625 pu real and reactive power respectively. Fig. 6 represents the convergence curve for PSO and CAPSO method. It is observed that CAPSO has better convergence.

VII. CONCLUSION

A methodology has been presented for optimum load-shed at selected buses so as to have adequate voltage stability margin and load bus voltages within limits. Sensitivities of line voltage stability index with respect to load-shed at buses have been used to identify buses for load shedding. Results have been obtained using PSO and one of its variant known as CAPSO. Similar results have

TABLE III
INITIAL SWARM OF FIVE PARTICLES FOR 25-BUS SYSTEM

SN	**Amount of load-shed in pu at selected bus**						Total Load-Shed **(pu)**
	Bus No.11	Bus No. 12	Bus No.18	Bus No. 19	Bus No. 23	Bus No. 24.	
1	0.093	0.234	0.371	0.366	0.370	0.326	1.7625
2	0.118	0.238	0.367	0.358	0.366	0.328	1.7768
3	0.106	0.240	0.371	0.367	0.371	0.324	1.7809
4	0.109	0.240	0.362	0.363	0.366	0.336	1.7789
5	0.105	0.231	0.362	0.366	0.361	0.334	1.7595

TABLE IV
OPTIMAL LOAD- SHED AT DIFFERENT BUSES FOR 25-BUS SYSTEM

Method	**Amount of load-shed in pu at selected bus**						Total Load-Shed **(pu)**
	Bus No. 11	Bus No. 12	Bus No. 18	Bus No 19	Bus No. 23	Bus No. 24	
PSO	0.039	0.115	0.282	0.347	0.325	0.375	1.484
CA-PSO	0.069	0.145	0.283	0.343	0.287	0.374	1.503

been obtained by both the optimization techniques but convergence characteristics of CAPSO are better than conventional PSO.

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L. D. Arya graduated in Electrical Engineering from SGSITS Indore and M.E. from BITS Pilani in 1972 and 1974, respectively. He received the Ph.D. degree in Power System Security from I.I.T. Delhi (India) in1991.

After serving BITS Pilani as faculty for a short duration he joined SGSITS Indore as a Lecturer in Electrical Engineering Department in 1977 and since 1996 he has been a Professor in the same institute. Dr. Arya is actively involved in research activities in the area of power systems security, optimization, soft computing, reliability assessment, and distribution generation. He has published more than 150 papers in national and international journals, conferences and guided a large number of candidates for Ph.D. He is also appointed as Non-executive Director of Distribution Company Western Region Government of Madhya Pradesh.

Dr. Arya has been conferred prestigious Power Gold Medal, Tata Rao Gold Medal and Pd. Madan Mohan Malviya Memorial Gold medal awards for his outstanding contribution in power system research. He is a fellow member of Institution of Engineers (India).

M. Shrivastava born in M.P. India in 1964. She graduated in Electrical Eng. from Devi Ahilya University, Indore, in 1985. She received the Ph.D. degree in Power System from RGPV University, Bhopal in 2009.

In 1990 she joined as a Lecturer at Govt. Eng. College Ujjain and was promoted as a Reader in 2001. She had been awarded 'Tata Rao Prize' by Institution of Engineers in 2006-2007. Her area of interest is power system. At present working as a Reader in Electrical Eng. Dept. at UEC Ujjain, India.

S. C. Choube was born in Jaunpur (India) in 1961. He received his BE and ME in Electrical Engineering from SGSITS Indore in 1982 and 1984 and Ph.D. from Devi Ahilya University Indore in 1998. He started his career as a Lecturer in Electrical Engineering Department of SGSITS Indore and joined as a Professor of Electrical & Electronics Engineering Department in University of Technology Rajiv Gandhi Technical University Bhopal (India). His research interests include power system security, optimization, and microprocessors applications. He was awarded Tata Rao and Pd. Madan Mohan Malviya Memorial Gold medal for his research papers.