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Optimal location of capacitors and capacitor sizing in a radial distribution system using Stud krill herd Algorithm

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Abstract: *This paper presents a new meta-heuristic technique, Stud Krill Herd Algorithm (SKHA) for solving capacitor placement problem in radial distribution system (RDS). The algorithm predicted the optimal size of the capacitors and should be placed at the proper location for loss minimization and hence improvement in voltage. The Stud krill herd algorithm is established along the biological herding behavior of krills along with genetic operators namely Stud selection and Crossover operator. The method is implemented in 69 IEEE RDS test system 94 bus Portugal system and the results are compared with other algorithms from the literature. The outcomes reveal the potency of the algorithm. The simulation is taken away on the MATLAB environment.*

Keywords**:** *Capacitor placement, Power loss minimization, Radial distribution system (RDS), Stud Krill herd algorithm (SKHA)*

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I. Introduction

In the radial distribution system, capacitors are primarily used for reactive power compensation. From the studies, 10 – 20% of total power generated is wasted in the form of ohmic losses at the distribution level. Reactive currents flowing in the network are the main source for these losses and are minimized by the usage of shunt capacitors. From [1], Capacitors are used for the minimization of power/energy losses, improvement of power factor, system security and maintenance of better voltage regulation. The main steps of this capacitor problem are (i) selection of number of capacitor units (ii) optimal location of capacitor units and (iii) sizing of capacitor units. Hence, getting the optimal position and size of capacitors plays a significant part in the planning and operation of an electrical system.

The authors [2] presented the overview of optimum shunt capacitor placement in distribution system based upon different methods and compared the results with Particle Swarm Optimization (PSO). The authors [3] gave a brief introduction and discussed various works done on the Shunt Capacitor Problem (SCP) till 2014. Also, they used two methods, namely sensitivity analysis for searching suitable locality of capacitors and Gravitational Search Algorithm (GSA) for selecting the size of capacitors. The authors [4] utilized the teaching – learning based optimization for selection of capacitor size and placement to minimize power loss and cost

The authors [5] proposed an integrated approach of loss sensitivity factor and voltage stability index for finding the optimal location of capacitor banks and Bacterial Foraging Optimization Algorithm (BFOA) for finding the optimal size of SC banks. In this paper [6], the location and size of capacitors are found by two bio – inspired algorithms bat algorithm and cuckoo search algorithm. In [7], the authors proposed loss sensitivity factor for selection of capacitor location and bat algorithm to select the size of capacitor. The authors [8] used power loss index for selecting the location and flower pollination algorithm to select the size of capacitor banks. Furthermore numerous solution techniques namely Ant colony optimization (ACO) [9], Shuffled frog leap algorithm (SFLA) [10], Modified monkey search algorithm [11], Whale optimization [12], Shark smell optimization [13], Hybrid PSO with Quasi Newton algorithm [14], Improved harmony Algorithm [15], Cuckoo search algorithm [16], Combined harmony search and particle artificial bee colony algorithm [17], Particle swarm optimization combined with Gravitational search algorithm [18] and Analytical approach [19] are developed for solving OCP problem.

This paper presents one of the new bio – inspired algorithm, namely Stud Krill herd algorithm is used for solving the capacitor optimization problem. RDS active power loss minimization is taken as an objective function subjected to various constraints namely voltage limit, reactive power limit and capacitor location and an optimum solution is obtained using SKH algorithm. The paper is organized as follows: (I) Introduction (II) Problem Formulation (III) Overview of Stud Krill herd algorithm (IV) Test system and Result analysis (V) Conclusion and finally References.

In 2012, Gandomi and Alavi [20], proposed a biologically inspired swarm intelligence algorithm. This method is based on the simulation of herding behavior of the large number of individual krills. Later in 2014, the same authors along with Wang [21], added updated genetic operators to KH method.

The main drawbacks in all the above methods are poor convergence speed and obtaining near optimal solutions. This paper is aimed to overcome all the above drawbacks by implementing one of the new bio – inspired, heuristic technique, Krill herd algorithm with stud operators namely Stud krill herd algorithm. In [22], the authors applied Stud krill herd algorithm for solving DG placement problem to achieve power loss minimization.

In this proposed approach, the following assumptions are taken:

- Harmonics effect is neglected.
- The system is within the acceptable balance tolerance.
- Bus 1 is always considered as slack/swing bus.

II. Problem Formulation

2.1 Power flow equation

2.1.1 Power loss equation

The forward – backward sweep algorithm based on Kirchhoff's laws is applied to find the power flow in the radial distribution system [23]. The real and reactive power loss equation is given by

$$P_L = P_{inj} - \sum_{a=1}^{n} P_D^a \quad (1)$$

where, P_{inj} – injected real power at bus 1; $P_{inj} = P_{Slack}$

$$Q_L = Q_{inj} - \sum_{a=1}^{n} Q_D^a \quad (2)$$

where, Q_{inj} – injected reactive power at bus 1; $Q_{inj} = Q_{Slack}$

2.1.2 Power loss after capacitor installation

Capacitors at optimal location reduce the system power loss, improve voltage stability and reliability. Total system power loss after capacitor installation is given by

$$Q_{LCap} = Q_{Slack} + \sum_{a=2}^{ncap} Q_{Cap}^a - \sum_{a=1}^{n} Q_D^a \quad (3)$$

where, n - number of buses, ncap – number of capacitor units connected

2.2 Objective function and Constraints

The objective function F of the radial distribution system comprises of minimization of power loss subject to various constraints.

$$F = \min (P_L) \quad (4)$$

2.2.1 Constraints

Voltage limit

The voltage magnitude should be within the minimum and maximum limits.

$$V^a_{min} < V^a < V^a_{max} \quad (5)$$

where, V^a_{min} – Minimum voltage limit (0.95 p.u.) and V^a_{max} – Maximum voltage limit (1.05 p.u.)

Reactive power limit

Q_{Cap}^a is the reactive power delivered from the capacitor and it should be within minimum and maximum limits.

$$Q_{Cap,min}^a \leq Q_{Cap}^a \leq Q_{Cap,max}^a \quad (6)$$

where, $Q_{Cap,min}^a$, $Q_{Cap,max}^a$ – minimum and maximum permissible limit of reactive power delivered from capacitor)

Capacitor location

Capacitors should be placed within the total number of nodes.

$1 < Cap_{loc} < n$; n = number of nodes (7)

2.3 Load model

Different load models are obtained by varying the factors α and β in the mathematical representation of the relationship between bus voltage and real and reactive power at bus a and is given by

$$P^a = \rho P_D^a V_a^\alpha \quad (8)$$

$$Q_a = \rho Q_D^a V_a^\beta \quad (9)$$

where, ρ - Load factor is varied by which the power demand is increased or decreased, α and β are load coefficients. The above factors are varied, in order to verify the usefulness of the algorithm in the practical execution. The values are as followed in Table (1):

Table (1) Load factors

Type of Load	ρ	α	β
Constant Power (CP) - Light	0.5	0	0
Constant Power (CP) - Nominal	1.0	0	0
Constant Power (CP) - Heavy	1.6	0	0
Constant Current (CC)	1.0	1	1
Constant Impedance (CI)	1.0	2	2
Industrial	1.0	0.18	6
Residential	1.0	0.92	4.04
Commercial	1.0	1.51	3.4

III. Overview Of Stud Krill Herd Algorithm

Stud krillherd algorithm is a heuristic technique developed by Gandomi et al. They first introduced Krillherd Algorithm (KHA) [20] which is based on the herding behavior of krills. The objective function used in KHA is determined by the distance between krill and food and the density of krills. In 2014, the same authors along with Wang introduced genetic reproductive schemes namely Stud selection and Crossover operator into KHA [21]. The aim of SKH is to accelerate convergence speed. The SSC operator is employed only to take the newly generating better solutions for each krill individual and to fine-tune the selected solution in order to improve its stability and robustness for global optimization. The proposed SKH approach can search the whole space widely by basic KH method and take out useful information by SSC operator. The flowchart for Stud krill herd algorithm application to capacitor problem is shown in Fig. (1) and the algorithm steps are as follows:

3.1 Stud krillherd algorithm steps

Begin

Step 1: Define the population size N and maximum iteration count I_{max}.

Initialization: Set The iteration Count I = 1; initialize the population X_i of N krill individuals; set the foraging speed V_f, the maximum diffusion speed D^{max}, and the maximum induced speed N^{max}; a probability of crossover p_c.

Step 2: Evaluating population. Evaluate the krill population based on its position.

Step 3: While I < I_{max} do

Sort all the krill according to their fitness.

for i=1:N (all krill) do

Perform the three motions.

1. *Movement induced by other krill individuals*

For each krill individual the movement is given by,

$$N_i^{new} = \left[N^{max} \left\{\sum_{j=1}^{NN}\left[\frac{K_i - K_j}{K_{worst} - K_{best}}\right]\left[\frac{X_j - X_i}{\|X_j - X_i\|+\varepsilon}\right]\right\}\left\{2\left(rand + \frac{I}{I_{max}}\right)\hat{K}_{I,best}\,\hat{X}_{I,best}\right\}\right] + \omega_n N_i^{old} \tag{10}$$

where, K_i – fitness value of the i^{th} krill individual (i = 1 to nk)
K_j – fitness value of the neighbor (j =1 to NN)
K_{worst} , K_{best} – worst and best fitness value of the krill individual
X – related position of the krill individual
ε – small positive number
N^{max} – maximum induced speed in ms^{-1}
I – actual iteration count
I_{max} – maximum iteration count
$\hat{K}_{I,best}$ – best fitness value of i^{th} krill
$\hat{X}_{I,best}$ – position corresponds to $\hat{K}_{I,best}$ of i^{th} krill
ω_n – inertia weight of the motion induced, in the range of (0,1)
N_i^{old} – last motion induced
rand – random number between 0 and 1

2. *Foraging activity*

The foraging motion depends on food location and previous experience about food location.

$$F_i = V_f\left\{2\left(1 - \frac{I}{I_{max}}\right)\hat{K}_{I,food}\,\hat{X}_{I,food} + \hat{K}_{I,best}\,\hat{X}_{I,best}\right\} + \omega_f F_i^{old} \tag{11}$$

Sensing distance is given by the equation

$$d_{s,i} = \frac{1}{5N}\sum_{j=1}^{N}\left\|X_i - X_j\right\|$$

If the distance between the krill individuals is less than the defined sensing distance, then they are neighbors.

where, N – number of krill individuals
V_f – foraging speed, ms^{-1}
ω_f – inertia weight of the foraging motion in the range (0, 1)
F_i^{old} – last foraging motion

3. *Physical diffusion*

The physical diffusion of the krill individual is a random process.

$$D_i = D^{max}\left(1 - \frac{I}{I_{max}}\right)\delta \tag{12}$$

where, D^{max} – maximum diffusion speed, $D^{max} \epsilon$ [0.01, 0.02] ms^{-1}
δ – random directional vector [-1 &1]

Apply mutation operator

$$X_{i,m} = \begin{cases} X_{gbest,m} + \mu(X_{p,m} - X_{q,m}) & rand_{i,m} < Mu \\ X_{i,m} & else \end{cases} \tag{13}$$

$Mu = 0.05/\hat{K}_{I,best}$

p, q ϵ {1,2, …i-1,i+1, …K} and μ is between 0 and 1

Update position for krill i by SSC operator as following

Perform selection operator

Choose the best krill (the Stud) for mating.

Implement crossover operator

$$X_{i,m} = \begin{cases} X_{r,m} & rand_{i,m} < C_r \\ X_{i,m} & else \end{cases} \tag{14}$$

$C_r = 0.2\,\hat{K}_{I,best}$

r ϵ{1,2, …i-1,i+1, …N}

Generate new krill X_i' by crossover.

Evaluate its quality/fitness K_i'.

if (K_i'< K_i) then do

Accept the new generated solution X_i' as X_i +1

else

Update the krill as X_i+1

The position vector is given by

$$X_i(t + \Delta t) = X_i(t) + \Delta t\,\frac{dx_i}{dt} \tag{15}$$

where $\Delta t = C_t\sum_{j=1}^{NV}(UB_j - LB_j)$

$$\frac{dX_i}{dt} = N_i + F_i + D_i$$

where, N_i – movement induced by other krill individuals
F_i – foraging activity
D_i – random diffusion
i =1 to nk nk – number of krill individuals
NV – total number of variables
C_t – constant between [0, 2]
UB, LB – upper and lower bound of the variables

If the related fitness value of each of the above mentioned effective vector (K_i, K^{best}, K^{food} or K_i^{best}) is better than the fitness of the i^{th} krill it has an attractive effect else repulsive effect.

end if

Check the limits and evaluate each krill based on its new position X_{i+1}.

end for i

Sort all the krill and find the current best.

I = I + 1;

Step 4: end while

Step 5: Output the best solutions.

End

3.2 Flowchart for the Stud Krill herd Algorithm application to OCP problem

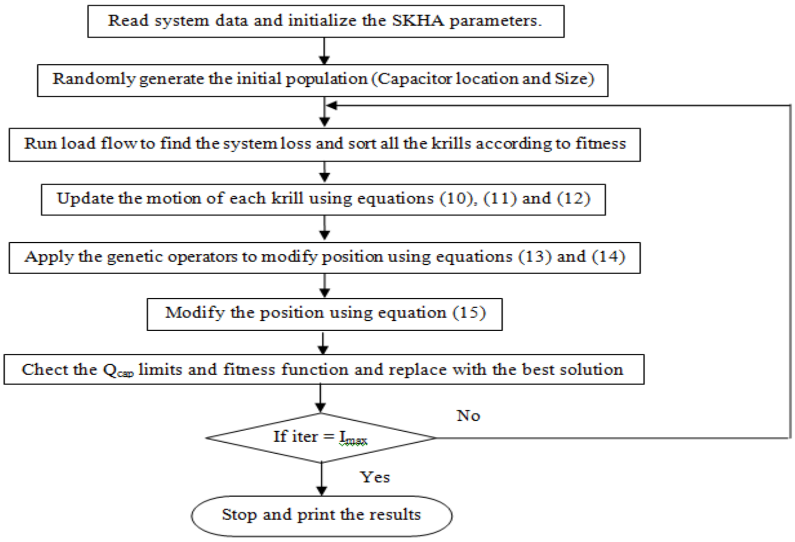

Fig. (1) Flowchart for the SKHA application to OCP problem

IV. Test System And Result Analysis

In order to verify the effectiveness of the proposed algorithm, it is implemented on the 69 bus IEEE radial test system and 94 bus Portuguese radial distribution systems. The software program is developed in MATLAB 2009a environment and executed on intel Core processor i3 – 2120 CPU with 3.30GHz. The various control parameters applied for SKHA are given in Table (2) and are common for all the test systems. For all the test systems, bus 1 is taken as slack bus. The load is varied as light (0.5), nominal (1.0) and peak (1.6) at full load condition and results are tabulated for all the test systems.

Table (2) Control Parameters

Number of krill individuals n_k	10
Maximum number of iterations I_{max}	100
Maximum induced speed N_{max}	0.01
Inertia weight of motion induced ω_n	0.9
Foraging speed V_f	0.02
Inertia weight of foraging motion ω_f	0.9
Constant C_t	0.5

4.1 Case 1: 69 – bus System

For the 69 bus RDS test system the base voltage is 12.66kV and the total load is (3.80 + j 2.69) MVA and the single line diagram is shown in Fig. (2). The proposed method is employed on 69 bus system and the power loss of the system without Capacitors is 220.534 kW. The proposed SKHA is used to find the optimal capacitor locations and sizes at different load levels; the acquired results are structured in Table (3). The graphical representation of network real power losses and voltage profile with multiple capacitors at different load levels are given in Fig (3) and Fig (4). After capacitor placement at nominal load condition (CP), the real power loss is reduced to 142.7028 kW and the minimum voltage is 0.932 at bus 65. The total kVAr capacity of the capacitor units is 3661kVAr. The results are compared with other methods which show the effectiveness of SKHA in the improvement of results and tabulated in Table (4).

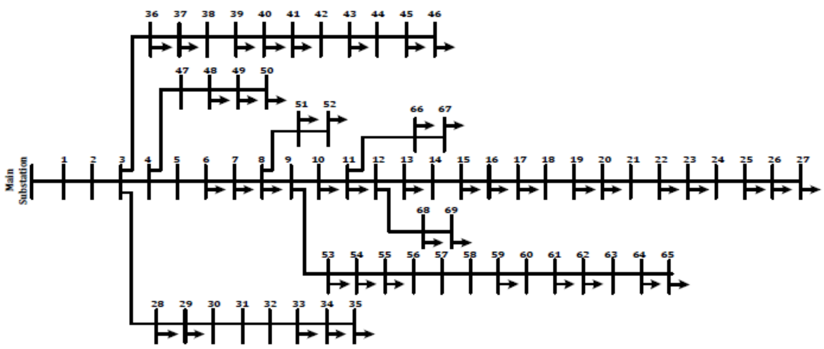

Fig (2) Single line diagram of 69 bus system

Table (3) Summary of results of 69 bus system with load variation

Parameters		69 bus system							
		CP load			CI load (1.0)	CC load (1.0)	Industrial	Residential	Commercial
		Light (0.5)	Nominal (1.0)	Peak (1.6)					
Load flow results	P_{loss} (kW)	50.6496	220.534	638.0838	156.5804	185.4969	168.5869	162.4031	154.7401
	Q_{loss} (kVAr)	23.0904	100.0281	251.4235	72.6461	85.0439	77.7154	75.1177	71.8449
	V_{min}	0.9573/65	0.9105/ 65	0.8469/ 65	0.9256/ 65	0.9184/ 65	0.9206/ 65	0.9227/65	0.9251/ 65
	V_{max}	0.9986/2,3, 28,26	1.0/ 2,28	0.9999/ 28,36	1.0/ 2,28	1.0/ 2,28	1.0/ 2,28	1.0/2,28	1.0/ 2,28
Capacitor location/ Size in kVAr		8/36	51/120	18/387	49/579	12/294	16/144	10/125	53/153
		12/30	36/1473	22/183	41/460	62/583	11/279	36/307	61/347
		61/327	60/337	11/183	12/368	50/146	7/271	62/430	64/225
		62/260	49/27	61/716	41/137	61/481	36/382	15/228	62/111
		36/222	19/211	62/610	46/98	37/75	58/245	61/406	59/289
		16/130	53/394	64/338	61/1061	17/148	61/504	28/277	16/278
		10/135	61/879	59/310	25/51	8/553	64/38	25/60	50/58
Ploss/kW		33.4626	142.7028	397.5023	102.492	120.3633	137.7941	122.3416	111.0032
Qloss/kVAr		15.671	65.5007	183.9776	47.7619	56.1587	64.2559	57.7173	52.4869
Vmin/busno.		0.9671/65	0.932/65	0.8867/65	0.9435/65	0.9386/65	0.9343/65	0.9372/65	0.9417/65
Vmax/busno.		1.0/ 2,3,4, 28,36,39	1.0/2,3,28, 36	1.0/2,28	1.0/2,3,28,36, 37,38,39,40,41, 42,43,44,45,46	1.0/2,3, 28,36	1.0/2,3, 28,36	1.0/2,3, 28,36	1.0/2,3, 28,36

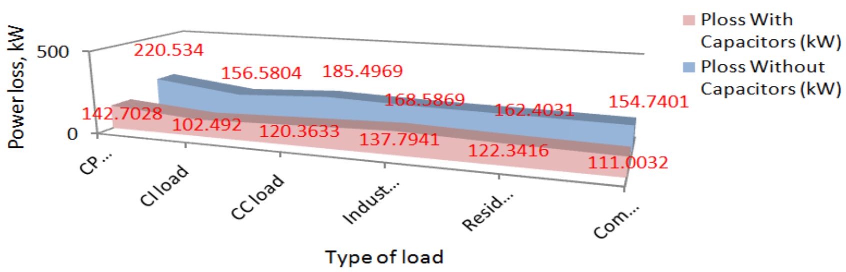

Fig. (3) Power loss reduction with Capacitors

Table (4) Comparison of results with other methods

Method	Power loss after capacitor installation, kW	% Reduction	V_{min}, pu
GSA [3]	145.9	35.16	0.9511
TLBO[4]	146.35	34.96	0.9313
FPOA [8]	145.777	35.2	0.9323
Fuzzy+SFLA [10]	152.3945	32.2703	NA
PSOGSA [18]	145.6945	35.2166	0.9330
Analytical approach [19]	147	34.66	0.931
Proposed SKHA	142.7028	35.2922	0.932

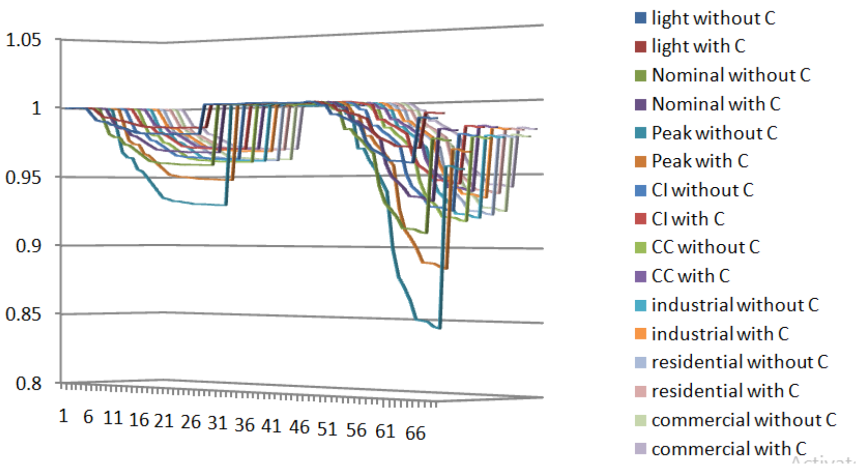

Fig. (4) Voltage profile improvement with Capacitors

4.2 Case 2: 94 – bus System

The base voltage of 94 bus Portuguese RDS test system is 15kV with a total load (4.797+ j2.324) MVA and the single line diagram is shown in Fig. (5). The power loss of the system without capacitors is 362.8578 kW. The proposed SKHA is employed to find the optimal capacitor locations and sizes; the acquired results are structured in Table (5). The graphical representation of network real power losses and voltage profile with multiple capacitors are given in Fig (6) and Fig (7). After capacitor placement the real power loss is reduced to 267.0254kW and the minimum voltage is 0.9106 at bus 92. The total kVAr capacity of capacitor unit compensation is 2431kVAr. At different load levels the performance of the system is also given in Table (5).

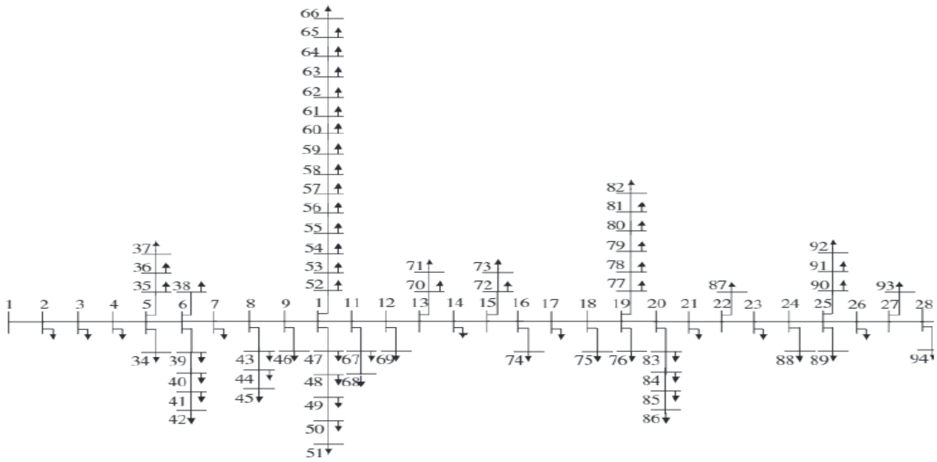

Fig (5) Single line diagram of 94 bus system

Table (5) Summary of results of 94 bus system with load variation

Parameters		94 bus system							
		CP load			CI load (1.0)	CC load (1.0)	Industrial	Residential	Commercial
		Light (0.5)	Nominal (1.0)	Peak (1.6)					
Load flow results	P_{loss} (kW)	79.6036	362.8578	1150.2	241.0107	277.4211	283.3123	249.0478	222.968
	Q_{loss} (kVAr)	110.9393	504.042	1587.3	301.143	387.9379	395.2676	348.9323	313.3502
	V_{min}	0.9299/ 91,92	0.8485/92	0.725/ 92	0.8868/ 92	0.8694/ 91, 92	0.8802/ 91,92	0.8834/ 91,92	0.8879/ 92
	V_{max}	0.9977/ 2	0.9951/2	0.9913/ 2	0.9961/2	0.9956/ 2	0.9961/2	0.9964/2	0.9962/ 2
Capacitor location/ Size in kVAr		24/199	18/333	69/473	8/290	75/249	58/250	41/83	70/150
		72/59	69/305	18/568	10/329	56/448	74/273	47/406	19/253
		58/172	25/237	77/671	77/164	52/253	40/149	13/341	58/102
		52/374	8/574	56/1111	25/253	24/345	21/226	38/350	47/185
		84/82	83/346	10/418	50/12	84/139	35/156	19/115	56/352
		61/48	47/260	59/387	58/568	12/194	7/121	26/110	8/275
		77/134	59/376	26/247	84/248	60/220	52/555	57/492	24/222
Ploss/kW		62.3677	267.0254	754.865	161.965	208.5133	252.8514	210.823	182.8317
Qloss/kVAr		86.5818	370.1304	1043.6	227.3268	290.7381	351.9495	294.3373	255.9842
Vmin/busno.		0.9564/ 91,92	0.9106/92	0.8476/92	0.9313/92	0.9192/ 91,92	0.9138/92	0.9196/ 91,92	0.924/92
Vmax/busno.		0.9986/2	0.9973/2	0.9951/2	0.9977/2	0.9973/2	0.9976/2	0.9977/2	0.9975/2

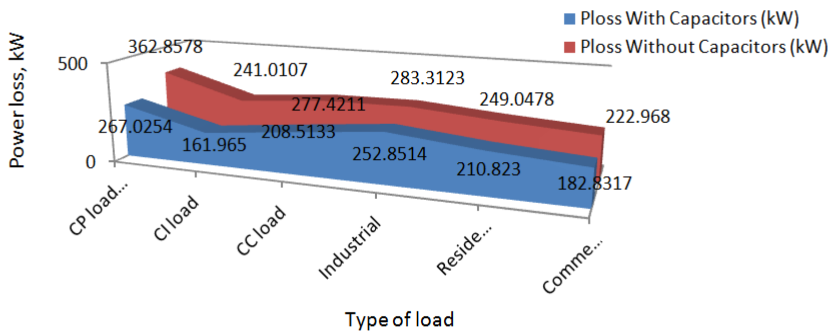

Fig. (6) Power loss reduction with Capacitors

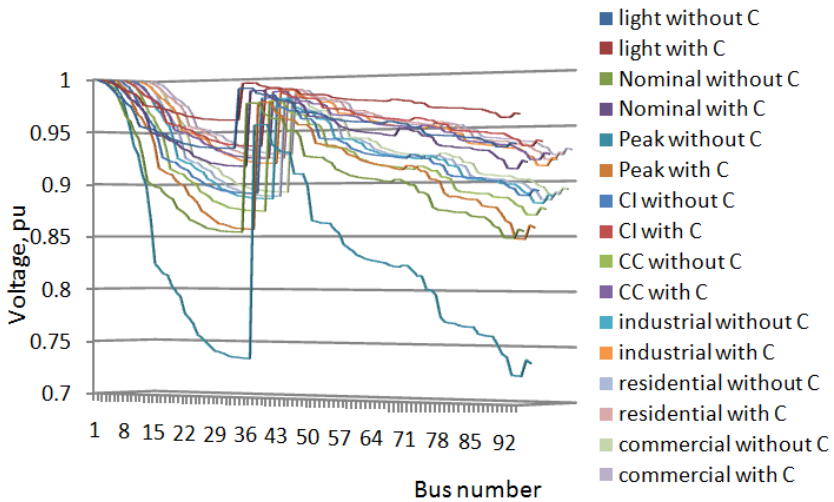

Fig. (7) Voltage profile improvement with Capacitors

V. Conclusion

This paper has presented Stud krill herd algorithm for capacitor placement and sizing problem in radial distribution system. From the results it is revealed that the algorithm gives the optimal solution when compared to other methods from literature. Real power losses of the system and reactive power losses at all the load levels have reduced noticeably. The results illustrate that including capacitors improve the voltage magnitude at all the buses. Based on the quality of outcome, it is concluded that Stud krill herd algorithm can be the hopeful technique for solving the optimal capacitor placement problem in radial distribution system.

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