Optimal capacitor placement and sizing in Radial Distribution System using PSO-HPSO methods with harmonics consideration

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Abstract — This paper presents new techniques for capacitor placement in radial distribution feeders, under dynamic load conditions with harmonics consideration, in order to reduce the real power loss, to improve the voltage profile and to achieve economical saving. The identification of the weak buses, where the capacitors should be placed is decided by a set of rules given by the fuzzy expert system. Power loss index and node voltage are used as inputs to the fuzzy expert system and the output is sensitivity index which gives the weak buses in the system where the capacitor to be placed. The sizing of the capacitors is modeled by an objective function to obtain maximum savings using Hybrid Particle Swarm Optimization (HPSO). To illustrate the applicability of the above algorithms, simulation is performed on an existing IEEE 34 bus distribution feeders. The results of the proposed approach are compared with PSO technique.

Key Words — Fuzzy expert system (FES), Harmonics, Hybrid Particle swarm optimization (HPSO),Particle swarm optimization (PSO), Radial distribution feeders (RDF).

I. INTRODUCTION

In the Radial Distribution Feeders (RDF), capacitors are installed at suitable locations for the improvement of voltage profile and to diminish the energy losses in the distribution system. It is estimated that as much as 13% of total power generation is dissipated as $\mathbf{I^2R}$ losses in the distribution networks [1]. Reactive currents flowing in the network account for a portion of these losses. By the installation of shunt capacitors, the losses produced by reactive currents can be reduced.

This is also vital for power flow control, improving system stability, power factor correction, voltage profile management, and reduction in active energy losses.

Hence it is essential to find the optimal location and size of capacitors required to maintain a nominal voltage profile and to reduce the feeder losses [4].

Ng et al. [1] presented the guidelines for the implementation of appropriate capacitor allocation techniques. Ng et al. [2] presented a novel approach using approximate reasoning to determine suitable candidate nodes in a distribution system for capacitor placement problem. The numerical procedure to determine the size of capacitors has been presented. Das [3] considered the capacitor as a constant reactive power load and as a constant impedance load. The genetic algorithm approach is used to size the fixed and switched capacitor for varying load conditions. Abdelsalam et al [5] considered the PSO and HPSO to find global optimal solution. The developed hybrid particle swarm optimization was integrated with a harmonic power flow algorithm to minimize the overall cost of the total real power loss.

Arunagiri et al [6] presents a multilayer feed forward ANN with error back propagation learning algorithm for the calculation of bus voltages and power loss for different harmonic components on a 33-bus Radial and the results are reported for various harmonics by which its viability for harmonic load flow assessment for radial systems has been indicated. For given a harmonic load, BPN gives the voltage solution with minimum time and maximum accuracy. Jong-Young Park et al [8] proposed a planning method for capacitor allocation in a distribution system considering the change in the annualized device installation costs. The relationship between the number of operations and the expected lifetime was formulated, and the total annualized costs, including the installation costs and the costs for real energy losses, were calculated using that relationship. The optimal solution for costs was determined using a GA.

A.Y.Chikhani et al [11] proposed a new method based on a heuristic technique for reactive loss reduction in distribution network is presented. This method allocates capacitors to certain nodes (sensitive nodes) which are selected by first identifying the branch which has the largest losses due to reactive power. Then, the node therein, which has the largest reactive power is selected. The capacitor rating is determined by differentiating the system losses with respect to the load connected to that node. The compensating capacitors are placed at these optimal locations with appropriate VAR ratings to achieve maximum benefits in dollar savings. The variation of the load during the year is considered. The capital and installation costs of the capacitors are also taken into account. Amgad A. EL-Dib et al [12] proposed a solution technique for finding the optimum location and sizing of the shunt compensation devices in transmission systems. The objective of the formulation is to improve the voltage stability of the system while maintaining acceptable voltage profile. The problem can be formulated as an integer nonlinear optimization problem. The newly developed evolutionary technique particle swarm optimization (PSO) is used to solve this problem.

Khodr H.M. et al[13] proposed a computationally efficient methodology for the optimal location and sizing of static and switched shunt capacitors in radial distribution systems. The problem is formulated as the maximization of the savings produced by the reduction in energy losses and the avoided costs due to investment deferral in the expansion of the network. The proposed method selects the nodes to be compensated, as well as the optimal capacitor ratings and their operational characteristics, i.e. fixed or switched. After an appropriate linearization, the optimization problem was formulated as a mixed-integer linear problem, suitable for being solved by means of a widespread commercial package.

In this paper, Fuzzy Expert System (FES) has been developed to identify the suitable locations for capacitor placement. The reason for using FES method is that the capacitor allocation problem is highly nonlinear in nature. Also, capacitor location at a particular bus depends on the values of power loss and voltage magnitude. The power loss and bus voltage exhibits a nonlinear relation. Owing to these facts, FES method is used in this work to address the capacitor allocation problem.

Hybrid Particle swarm Optimization (HPSO) is used to solve the capacitor sizing problem with harmonics for dynamic load. Although capacitor sizing is discrete in nature, it is necessary to select the capacitor size at suitable locations within a narrow band, necessitating the need for a continuous optimization procedure. The capacitors sizing are designed with the objective function, which minimizes the power loss in the feeders. The proposed method has been tested on an existing IEEE 34 bus system.

Figure 1 illustrates the flow diagram of the proposed work as shown below,

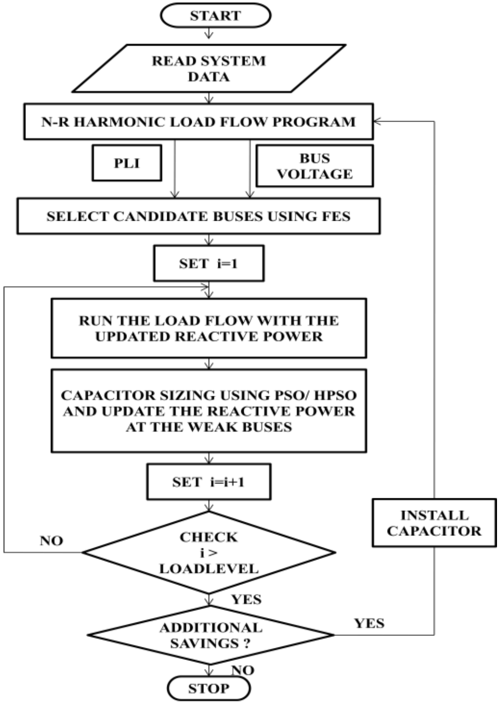

Fig 1. Framework of the approach

II. PROBLEM FORMULATION AND IMPLEMENTATION

The entire framework of the approach to solve the optimal capacitor allocation problem includes the use of numerical procedures, coupled to the Fuzzy Expert System (FES) [2]. Initially, a load flow program is used to calculate the power loss reduction by compensating the total reactive load current at every node of the distribution system. The loss reductions are then linearly normalized into [0, 1] range with the largest loss reduction having a value of 1 and the smallest one having a value of 0.

The power loss reduction indices at various nodes along with the per-unit node voltages are the inputs to FES, which determines the suitable node for capacitor installation by fuzzy inferencing method. The savings function S, is maximized by the capacitor sizing algorithm [5] .The above procedure is repeated until no further additional savings from the capacitor installations are achieved. The capacitor sizing procedure takes into account the discrete nature of the capacitor sizes and the piecewise cost function. Figure 1 illustrates the flow diagram of the proposed work.

A. Radial main feeder test system

An IEEE 34-bus radial distribution system and the single line diagram[2] of the feeder comprising branches / node are shown in Figure 2 & Table 1 .

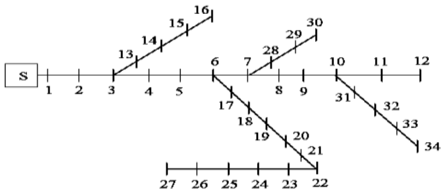

Fig 2. IEEE 34-Bus Test System

TABLE I
TEST SYSTEM SPECIFICATIONS

Radial feeder type	IEEE 34-BusSystem
Base KV	11 KV
Base MVA	100 A

B. Objective function for capacitor sizing

The size of the capacitor to be installed at the selected locations in the feeder system is estimated by minimizing the following objective function [3].

$$\min C = K_e \sum_{j=1}^{L} T_j P_j + \sum_{i=1}^{ncap} (K_{cf} + K_c Q_{ci}) \qquad (1)$$

Where,

C - Savings in '$'.

Ke - Energy Cost of Losses (0.06$/KWh).

Pj - Power loss (KW).

Tj - Time duration (seconds).

L - Number of load level.

ncap - Number of Capacitor locations.

Kcf - Capacitor Installation Cost (1000$).

Kc - Capacitor Marginal Cost (3$/KVAr).

Qci - Reactive power injection from capacitor to node i.

The total real power loss is defined by [5],

$$P_{loss} = \sum_{i=1}^{nb} P_{loss}{}_{i}^{(1)} + \sum_{i=1}^{nb} \sum_{h=h0}^{hmax} P_{loss}{}_{i}^{(h)} \qquad (2)$$

Where,
n - Number of branches.
h0 - smallest harmonic order of interest.
hmax - highest harmonic order of interest.

Constraints :

a) Capacitor limit constraints

$$Q_{cmin} \leq Qc \leq Qcmax$$

Where,
Q_{cmin} = Minimum rating of capacitor.(150 KVAr)
Q_{cmax} = Maximum rating of capacitor.(1000 KVar)

b) Voltage limit constraint

$$V_{min} \leq V \leq V_{max}$$

Where,
V_{min} =Minimum value of voltage in pu (0.9pu).
V_{max} =Maximum value of voltage in pu (1.1pu).

C. Mathematical formulation for savings

The savings function NS [7], maximized by this capacitor sizing algorithm is given by,

$$\boldsymbol{NS = KP + KF + KE - KC} \qquad (3)$$

Where,

- NS = Net Savings ($)

- KP = Benefits due to released demand (KW)

KP = ΔKP * CKP * IKP (3.1)

ΔKP - Reduced demand (KW)
CKP - Cost of generation (taken as $200/KW)
IKP - Annual rate of generation cost (taken as 0.2)

- KF = Benefits due to released feeder capacity(KVA)

KF = ΔKF * CKF * IKF (3.2)

ΔKF - Released feeder capacity (KVA)
CKF - Cost of feeder (taken as $3.43/KVA)
IKF - Annual rate of cost of feeder (taken as 0.2)

- KE = Benefits due to savings in energy (KWh)

KE = ΔKE * r (3.3)

ΔKE - Savings in Energy (KWh)
r - Rate of energy (taken as $0.06/KWh)

- KC = Cost of installation of capacitor ($)

KC = Qc * ICKC * IKC (3.4)

Qc - Total KVAr
ICKC - Cost of capacitor (taken as $4/KVAr)
IKC - Annual rate of cost of capacitor (taken as 0.2)

D. Harmonic load flow solution – NR method

Newton-Raphson method is an iterative method which approximates the set of non-linear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to first approximation.

In presence of harmonics, lines are represented by a series impedance as z (h) =R+j h X_L Bus data and line data are given as inputs to the load flow program by Newton-Raphson (N-R) method. The load flow solution gives power loss and voltage level at each bus which is taken for further analysis.

III. CAPACITOR PLACEMENT

The FES contains a set of rules, which are developed from qualitative descriptions. In a FES, rules may be fired with some degree using fuzzy inferencing; whereas, in a conventional expert system, a rule is either fired or not fired. For the capacitor allocation problem, rules are defined to determine the suitability of a node for capacitor installation. For determining the suitability of capacitor placement at a particular node, a set of fuzzy rules has been established. The inputs to the rules are the voltage and power loss indices, and the output is the suitability of capacitor placement. The rules are summarized in the fuzzy decision matrix [2]. These fuzzy variables described by linguistic terms are represented by membership functions. The membership functions for power loss index, bus voltage and sensitivity index are shown in Table 2.

$$PLI_{(n)} = \frac{(Lossreduction_{(n)} - Lossreduction_{(mi}}{(Lossreduction_{(max)} - Lossreduction_{(m}} \quad (4)$$

TABLE 2

MEMBERSHIP FUNCTION FOR FUZZY EXPERT SYSTEM

Variable	Power Loss Index	Bus Voltage	Sensitivity Index
Low	<0.25	<0.94	<0.25
Low-Medium	0-0.5	0.92-0.98	0-0.5
Medium	0.25-0.75	0.96-1.04	0.25-0.75
High-Medium	0.5-1	1.02-1.08	0.5-1
High	>0.75	>1.1	>0.75

The decision matrices formed in the fuzzy expert system for the capacitor placement problem identified in this work are shown in Table 3.

TABLE 3

DECISION MATRIX FOR DETERMINING SUITABLE CAPACITOR LOCATION (PLI VS VOLTAGE)

AND		VOLTAGE				
		LOW	LOW MEDIUM	MEDIUM	HIGH MEDIUM	HIGH
PLI	LOW	LOW MEDIUM	LOW MEDIUM	LOW	LOW	LOW
	LOW MEDIUM	MEDIUM	LOW MEDIUM	LOW MEDIUM	LOW	LOW
	MEDIUM	HIGH MEDIUM	MEDIUM	LOW MEDIUM	LOW	LOW
	HIGH MEDIUM	HIGH MEDIUM	HIGH MEDIUM	MEDIUM	LOW MEDIUM	LOW
	HIGH	HIGH	HIGH MEDIUM	MEDIUM	LOW MEDIUM	LOW MEDIUM

IV. CAPACITOR SIZING

A. Particle Swarm Optimization

Particle swarm optimization is a population based stochastic optimization to treat problems with discrete variables. This feature enables the application of PSO in evaluating the capacitor sizing based on objective function.

B. Parameters Used

$C_1=1$, $C_2=1$; $W_{min}=0.2$, $W_{max}=0.9$; $Q_{min}=150$, $Q_{max}=1000$;

Population Size = 50;

Number of iterations = 100.

C. Steps in PSO Algorithm

Step 1: Generate the random population at candidate nodes for size(s) of capacitors with random positions.

Step 2: Perform the load flow to determine various node voltages, active power losses.

Step 3: Calculate the fitness value as given by the objective function for each particle.

Step 4: Initialize the pbest and the gbest values.

Step 5: Update the velocity and position of particle using the following equations respectively and check for boundary limit of capacitors.

$$V_{d+1} = [\omega * V_d + C_1 * rand() * (P_{best} - X_d) - C_2 * rand() * (G_{best} - X_d)]$$

$$X_d = X_d - V_{d-1}$$

Step 6: Perform load flow and evaluate fitness value for each new set of particles.

Step 7: Repeat from step 4 till the stopping criteria
is reached. Here, stopping criteria is assumed as maximum iteration of 100.

D. Hybrid Particle Swarm Optimization

There has been a lot of research in improving the performance of the PSO with respect to the speed of convergence. The improvements in the PSO are done by trying to have the properties as in the GA beside the PSO own properties. One of the most powerful properties of the GA is the ability to breed and produce better individuals (children) than the old ones (parents).This model incorporates one major aspect of the standard GA into the PSO, which is the reproduction or breeding.

E. Steps in HPSO Algorithm

Step 1:Generate the random population at candidate nodes for size(s) of capacitors with random positions.

Step 2: Perform the load flow to determine various node voltages, active power losses.

Step 3: Calculate the fitness value for the given objective function for each particle.

Step 4: Set the pbest and the gbest value.

Step 5: Update the velocity and position of particle using the above equations respectively.

$$V_{d+1} = [\omega * V_d + C_1 * rand() * (P_{best} - X_d) - C_2 * rand() * (G_{best} - X_d)]$$

$$X_d = X_d - V_{d-1}$$

Step6: Perform the breeding process using following Equation and further updating the velocity and position of particle.

For position vectors of the child,

$$child_1(x_i) = p_i * parent_1(x_i) - (1 - p_i) * parent_2(x_i)$$
$$child_2(x_i) = p_i * parent_2(x_i) - (1 - p_i) * parent_1(x_i)$$

For the velocity vectors of the child,

$$child_1(v) = \frac{parent_1(v) + parent_2(v) * |parent_2(v)|}{|parent_1(v) * parent_2(v)|}$$

$$child_2(v) = \frac{parent_1(v) + parent_2(v) * |parent_1(v)|}{|parent_1(v) * parent_2(v)|}$$

Step 7: Perform the load flow and evaluate fitness value of objective function for each new set of particles.

Step 8: Repeat from step 4 till the stopping criteria is reached. Here stopping criteria is maximum 100 iteration.

V. DYNAMIC LOADING

The load pattern plays an important role in the efficient installation of capacitors in a distribution system. Using the exact load data is difficult in planning, forecast data must be used. The annual load is divided into three categories: [8]

- Summer
- Winter
- Spring / Fall

TABLE 4
ANNUAL LOAD DATA

LOAD LEVEL		AMOUNT (% of base load)	DURATION (Hrs.)
SUMMER	LOADhigh	1.40	547.5
	LOADmid	1.00	876
	LOADlow	0.80	547.5
WINTER	LOADhigh	1.15	876
	LOADmid	0.95	876
	LOADlow	0.70	438
SPRING	LOADhigh	0.90	1314
	LOADmid	0.75	2190
	LOADlow	0.40	876

VI. RESULTS AND DISCUSSION

Simulation is carried using MATLAB-7 software and the results are obtained.

TABLE 5
TOTAL SAVINGS

LOAD LEVEL	**PSO**		**HPSO**	
	Without harmonics	*Without harmonics*	*Without harmonics*	*Without harmonics*
1.4	30918	145670	30299	145770
1	18706	81732	18816	81901
0.8	9899	39639	9958	39722
1.15	24873	113310	24967	113420
0.95	16915	72746	16997	72850
0.7	7146	27229	7193	27280
0.9	18871	81556	18961	81711
0.75	18181	77129	18263	77293
0.4	3173	3281	3281	11152

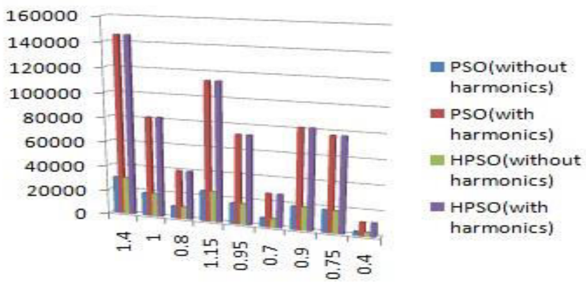

Fig 3. Comparison of savings in HPSO over PSO.

TABLE 6

SUMMARY OF IEEE 34 BUS RDS WITH DYNAMIC LOADING CONDITION CONSIDERING HARMONICS

S.NO	LOAD LEVEL	TOTAL KVAR		BEFORE PLACEMENT (PU)		AFTER PLACEMENT (PU)				% OF INCREASE IN VOLTAGE		% OF DECREASE IN P-LOSS	
						PSO		HPSO					
		PSO	HPSO	AVG. VTG.	AVG. P-LOSS.	AVG. VTG.	AVG. P-LOSS.	AVG. VTG.	AVG. P-LOSS.	PSO	HPSO	PSO	HPSO
1	1.4	**2985**	**2948**	0.95907	1.9418	0.96658	1.3848	0.96649	1.3846	**0.7770**	**0.7677**	**28.68**	**28.70**
2	1.0	**2111**	**2061**	0.97409	0.9239	0.97921	0.67825	0.97909	0.67784	**0.5229**	**0.5107**	**26.59**	**26.63**
3	0.8	**1665**	**1631**	0.98136	0.57299	0.98533	0.42567	0.98525	0.42544	**0.4029**	**0.3948**	**25.71**	**25.75**
4	1.15	**2422**	**2391**	0.96854	1.2528	0.97449	0.91039	0.97441	0.9101	**0.6106**	**0.6024**	**27.33**	**27.35**
5	0.95	**1991**	**1954**	0.97592	0.82713	0.98073	0.60898	0.98064	0.60874	**0.4905**	**0.4813**	**26.37**	**26.40**
6	0.70	**1449**	**1425**	0.98493	0.43216	0.98836	0.32281	0.9883	0.32267	**0.3470**	**0.3410**	**25.30**	**25.34**
7	0.90	**1890**	**1844**	0.97774	0.7365	0.98228	0.54389	0.98218	0.54367	**0.4622**	**0.4521**	**26.15**	**26.18**
8	0.75	**1563**	**1527**	0.98315	0.49982	0.98686	0.37237	0.98678	0.37213	**0.3759**	**0.3679**	**25.50**	**25.55**
9	0.4	**845**	**810**	0.99545	0.13524	0.99745	0.10409	0.99737	0.10363	**0.2005**	**0.1925**	**23.03**	**23.37**

TABLE 7
COMPARISON OF HPSO SAVINGS WITH PSO

SAVINGS ($)		Standard Deviation	Average Value	Best value	Worst value
PSO	***Without harmonics***	99.82	147930	148024	147748
	Without harmonics	180.04	649940	650115	649590
HPSO	***Without harmonics***	85.1781	148650	148735	148472
	Without harmonics	141.7823	650980	651101	650694

INCREASE IN SAVINGS ($) : (HPSO over PSO)

Savings ($)	**Average Value ($)**
WITHOUT HARMONICS	720
WITH HARMONICS	1040

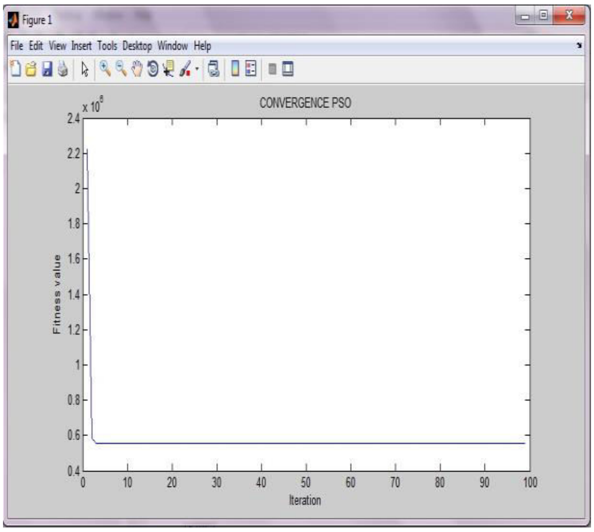

Fig 3(a). Convergence characteristics of PSO

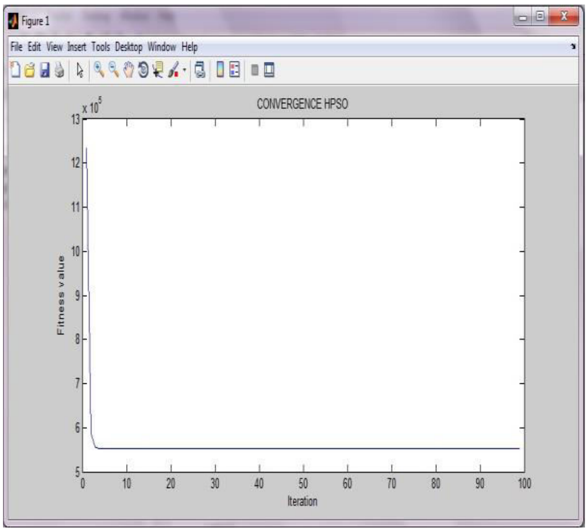

Fig 3(b). Convergence characteristics of HPSO

VII. CONCLUSION

This paper has discussed the combined method of FES & HPSO to determine optimal capacitor placement in radial distribution system for energy loss minimization and annual cost savings maximization considering harmonics under dynamic loading conditions. The use of FES determines the nodes for capacitor allocation by finding a compromise between the loss reduction from capacitor installation and voltage level improvement. In addition, the FES can easily be adapted for capacitor allocation in distribution system planning, expansion and operation. Using Hybrid Particle Swarm Optimization algorithm, the optimal size of capacitor is obtained for both cases and saving in cost realized due to capacitor placement. The time varying characteristics of the load are also considered.

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