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ANALYSIS OF RADIAL DISTRIBUTION SYSTEM OPTIMIZATION WITH FACTS DEVICES USING HYBRID HEURISTIC TECHNIQUE

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ABSTRACT

Distribution networks transport electric energy to the end user from distribution substations. Power utilities are looking for improved power delivery performance. The performance of the delivery system is measured by the power loss of the system. The increase in power loss increases the operating cost of the distribution system. This paper presents an algorithm to minimizing the power loss of the distribution system. Self Adaptive Hybrid Differential Evolution (SaHDE) technique combined with sensitivity factors has been practiced to find the optimal location and the size of FACTS devices to reduce the operating cost of Radial Distribution System (RDS). The locations of the FACTS devices are located by the sensitivity factors. The amount of reactive power component generation/absorption by the FACTS devices at the identified locations has been calculated through SaHDE. The effectiveness of the proposed technique is validated through 10-bus, 34-bus and 85-bus radial distribution systems.

Keywords: *Distribution Systems, FACTS, Loss Reduction, Loss Sensitivity Factors, SaHDE.*

1. INTRODUCTION

For More than five decades, the power loss in distribution system has been reduced through the network reconfiguration and/or by allocation of capacitor banks. Network reconfiguration is the process of changing the topology of distribution systems by changing the open/close status of switches. The load at the feeder can be transferred as a result of altering the open/close status of the switches [1 - 3]. However, there are numerous switches in a typical distribution system and the number of possible switching operations is tremendous. Considering this complexity, the capacitor placement has been carried out for loss reduction as an alternative practice. There are various practices have been followed in finding the location of the capacitor banks and the amount of capacitor banks switched on/off to the identified location in the distribution systems. Duran [4] have developed the procedure for capacitor placement through dynamic programming and assumed the capacitor sizes as discrete variables. Grainger et al.[5] introduced nonlinear programming for capacitor placement, where variables were treated as continuous. Baran and Wu [6] proposed a method for capacitor placement using mixed integer programming. The substation level voltage control with dynamic re-sizing of capacitors has been dealt in [7]. Many other optimization methods such as genetic algorithm [8-10], Particle Swarm Optimization [11], Plant Growth Simulation Algorithm [12], tabu search [13], heuristic search techniques [14-16] had been proposed in recent years for capacitor placement problem. Capacitor placement problem has been viewed as multi-constraint problem and the constraints were effectively handled through fuzzy reasoning approach [17]. Farahai et al. [18] has proposed a method combining both capacitor placement and reconfiguration for loss reduction.

The nature of the distribution system is normally dynamic and will have change in load conditions. Therefore, maintaining the voltage at the buses within the limit also has great importance with power loss reduction under dynamic load demand. The control of reactive power under different loading conditions has been achieved with the combination of fixed and switched capacitors. Though the combination brings variable reactive power, it falls short to discharge the exact requirement. In addition, capacitors with inductive components produce ferroresonance.

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In order to overcome the above mentioned short comings, power electronic devices with the improvements in current and voltage handling capabilities (Flexible AC Transmission System-FACTS) have been incorporated. The concept of FACTS devices was originally developed to control reactive power for transmission systems, but it has been introduced recently in distribution systems. Dynamic Voltage Restorer (DVR) is a series connected converter which is used to compensate some of the power quality problems such as voltage sag, voltage unbalance [19-23] which occurs in short duration in millisecond range. In this duration, DVR can inject both active and reactive power to the system for compensation of sensitive loads and active power injection into the system must be provided by energy storage system. Series Static Voltage Restorer (SSVR) was utilized for the improvement of power quality in [24].

In this paper, Static VAR Compensator (SVC), Thyristor-Controlled Series Capacitor (TCSC) and Unified Power Flow Controller (UPFC) are analyzed with distribution system for optimization. The conventional loss sensitivity factors are introduced to identify the optimal location of FACTS devices in the distribution system and the amount of reactive power injection/absorption are fine-tuned with the help of SaHDE in order to accomplish dynamic load variation.

2. PROBLEM FORMULATION

In this paper, the objective of FACTS devices placement in the distribution system is to minimize the total annual cost of the system subject to radial constraint, branch current capacity and bus voltage constraints in which all loads must be energized. The objective function of the problem is mathematically defined in (1),

$$F = \min (AC) \quad (1)$$

Subject to

$$|V_{min}| < |V_i| < |V_{max}|$$
$$|I_{max,j}| > |I_j|$$

where,

AC (Annual Cost)= $P_{loss,cost}$+ FACTS $_{cost}$

$P_{loss,cost}$ = Energy Loss Cost

$FACTS_{cost}$ = FACTS Placement cost

i = 1,2…….nb;

nb = Total number of buses present in RDS

j = 1,2,…….nl;

nl = Total number of lines present in RDS

V_{max}= Maximum voltage limit assumed as 1.0 pu

V_{min} = Minimum voltage limit assumed as 0.9 pu

2.1 Estimation Power Loss Cost

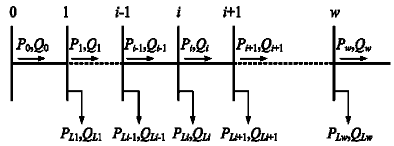

Figure 1: Single Line Diagram of a Main Feeder

Considering the single line diagram in figure 1, for calculating the energy loss cost of the distribution system, the following set of load flow equations (2), (3) and (4) are used.

$$P_{i+1} = P_i - P_{Li+1} - R_{i,i+1} \frac{P_i^2 + Q_i^2}{V_i^2} \quad (2)$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,i+1} \frac{P_i^2 + Q_i^2}{V_i^2} - V_i^2 \frac{y_i}{2} \quad (3)$$

$$V_{i+1}^2 = V_i^2 - 2(R_{i,i+1} P_i + X_{i,i+1} Q_i) + (R_{i,i+1}^2 + X_{i,i+1}^2) \frac{P_i^2 + Q_i^2}{V_i^2} \quad (4)$$

where,

P_i and Q_i are the real and reactive powers that flow out of bus i;

P_{Li} and Q_{Li} are the real and reactive load powers in bus i

The resistance and reactance of the line section between buses i and i+1 are denoted by $R_{i,i+1}$ and $X_{i,i+1}$ respectively.

$\frac{y_i}{2}$ is the total shunt admittance at bus i

The power loss P_{Loss} (i, i+1) of the line section connecting buses i and i+1 is given in equation (5)

$$P_{Loss}(i, i+1) = R_{i,i+1} \frac{P_i^2 + Q_i^2}{V_i^2} \quad (5)$$

The power loss $P_{F,Loss}$ of the feeder may be determined by summing the losses of all line sections of the feeder, given in (6),

$$P_{F,Loss} = \sum P_{Loss}(i,i+1) \quad (6)$$

The total system power loss $P_{T,Loss}$ is the sum of power losses of all feeders in the system. The total energy loss cost has been calculated as,

P_{loss_cost}=$P_{T,loss}$ * K_p; where K_p is the equivalent annual cost of power loss in \$/(kW-year) assumed as 168 \$/(kW-year)

2.2 Estimation of FACTS Devices Cost

The installation cost of FACTS is given by (7). The cost for installation has been taken from [25] and [26].

$$\left.\begin{aligned} C_{SVC} &= 0.0003S^2\text{-}0351S+127.38 \\ C_{TCSC} &= 0.0015S^2\text{-}7130S+153.75 \\ C_{UPFC} &= 0.0003S^2\text{-}2691S+188.22 \end{aligned}\right\} \quad (7)$$

where,

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S - Operating range of the FACTS devices in MVAR

The value of S, calculated using equation (8),

$$S=|Q_2|-|Q_1| \quad (8)$$

where,

Q_2 - Reactive power flow in the line after installing FACTS device in MVAR

Q_1 - Reactive power flow in the line before installing FACTS device in MVAR.

The cost is optimized with the following constraint is given in (9) and (10).

$$-100MVAR \leq Q_{SVC} \leq 100MVAR \quad (9)$$

$$-0.8X_L \leq X_{TCSC} \leq 0.2X_L \quad (10)$$

For UPFC equation (9) and (10) are considered. Where, X_{TCSC} is the reactance added to the line by placing TCSC, X_L the reactance of the line where TCSC is located and Q_{SVC} is the reactive power injected at the bus by placing SVC.

3. PROPOSED ALGORITHM

For the FACTS placement, the candidate nodes for placement are determined using the loss sensitivity factors. The amount of reactive power injection through FACTS to the candidate nodes has been determined using the SaHDE algorithm [27].

3.1 Analysis on Finding Optimal Location of FACTS Devices

During the early stages, the identification of candidate nodes for FACTS devices placement was carried out through the experience of the engineers and the historical analysis. Then sensitivity analysis has been incorporated in order to reduce the search space and precise solution for indentifying the location. The sensitivity analysis is a conventional procedure to find out the locations with maximum impact on the system real power losses with respect to the node reactive power. The figure 2 illustrates a distribution line with a series impedance of R+jX connected between buses ‘p’ and ‘q’, and an effective load of $P_{eff} + jQ_{eff}$ at bus ‘q’. The term ‘eff’ mentioned in the subscript refers the total load connected beyond the referred bus.

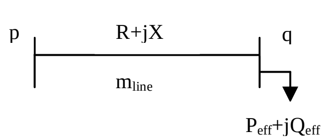

Figure 2: Single Line Diagram of a Distribution Line

The active power loss for m^{th} line is given in equation (11),

$$P_{lineloss}[q] = \frac{(P_{eff}^2[q] + Q_{eff}^2[q])R[k]}{(V[q])^2} \quad (11)$$

The loss sensitivity factor can be obtained from equation (12),

$$\frac{\partial P_{lineloss}}{\partial Q_{eff}} = \frac{2Q_{eff}[q] * R[k]}{(V[q])^2} \quad (12)$$

With the help of load flow equations, the loss sensitivity factor of all lines are calculated and arranged in descending order of the given system. From this sequence, the end bus of lines which have less than normalized voltage are considered as weak buses and must need the voltage improvement at the location.

3.2 SaHDE Algorithm for Identifying FACTS Sizes

The purpose of introduction of SaHDE is to find the optimum amount of reactive power injection through FACTS to be included in the identified optimal location of the distribution system. The pseudocode of the SaHDE algorithm has been given below,

```
// Pseudocode for SaHDE
Let iteration t= 0;
Initialize F_Mean=0.5, F_Variance=0.1, CR_Mean=0.5,
CR_Variance=0.1;
Initialize population number (Np) and the maximal iteration
number (Niter),total variable (Nv)
/* Population initialization */
for(pop=1;pop<=Np;pop++)
for( var=1;var<=Nv;var++)
G[pop][var]=getRandom(var_min,var_max,random);
do
{
for(pop=1;pop<= Np;pop++)
{
/* Mutation operation*/
j_row=getRandom(1,pop,random);
k_row=getRandom (1,pop,random);
for( var=1;var<= Nv;var++)
//Calculate F_Gaussian
Gplus[pop][var]=G[pop][var]+F_Gaussian*
        (G[pop][j_row]-G[pop][k_row])
/* Crossover operation*/
for( var=1;var<= Nv;var++)
{
 if(getRandom()>CR_Gaussian)
 G_plus=G;
 }
```

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```
/* objective calculation */
if(f(G)>f(Gplus))
{
for( var=1;var<= N_v;var++)
G=Gplus;
CRI_Final[t]=CRI[pop];
}}
Obj_new=min(f(G),f(Gplus));
final_population=pop;
 /* Acceleration */
if(Obj_new ==Obj_old)
{
for(pop=1;pop<= N_p;pop++)
for( var=1;var<= N_v;var++)
G=G-(int) Math.round(α*gradient(Obj_new));
}
else
Obj_old=Obj_new;
/* Migration */
for( pop=1;pop<=N_p;pop++)
{
  if(pop!=final_population)
  for(var=1;var<=N_v;var++)
    if(G[pop][var]==G[final_population][var])
    ny=ny+0;
    else
 ny=ny+1; }
ro=ny*1.0/(total_loop*(population-1));
ro2=getRandomm();
ro3=getRandomm();
if(ro<0.3)
 for( pop=1;pop<=N_p;pop++)
     if(pop!=final_population)
     for(var=1;var<=N_v;var++)
     {
     roo3=((G[final_population][var]-
            vmin[var])*1.0/(vmax[var]-vmin[var]));
     if(ro3<roo3)
      G[pop][var]=G[final_population][var]+
                  (ro2*(vmin[var]-
                  G[final_population][var]));
     else
      G[pop][var]=G[final_population][var]+
                (ro2*(vmax[var]-
                 G[final_population][var]));
CR_MEAN=Mean (CRI_Final,t);
iter=iter+1;
} while(iter<N_iter)
```

4. COMPUTATIONAL FLOWCHART

The optimal FACTS placement process starts with identifying the locations by using sensitivity factors. The optimal sizes at the optimal locations are received through SaHDE. The identified number of locations is considered as variables for the SaHDE. The optimum size of FACTS has been fine tuned through SaHDE. The flowchart for the proposed method based on the SaHDE algorithm is given in the figure 3.

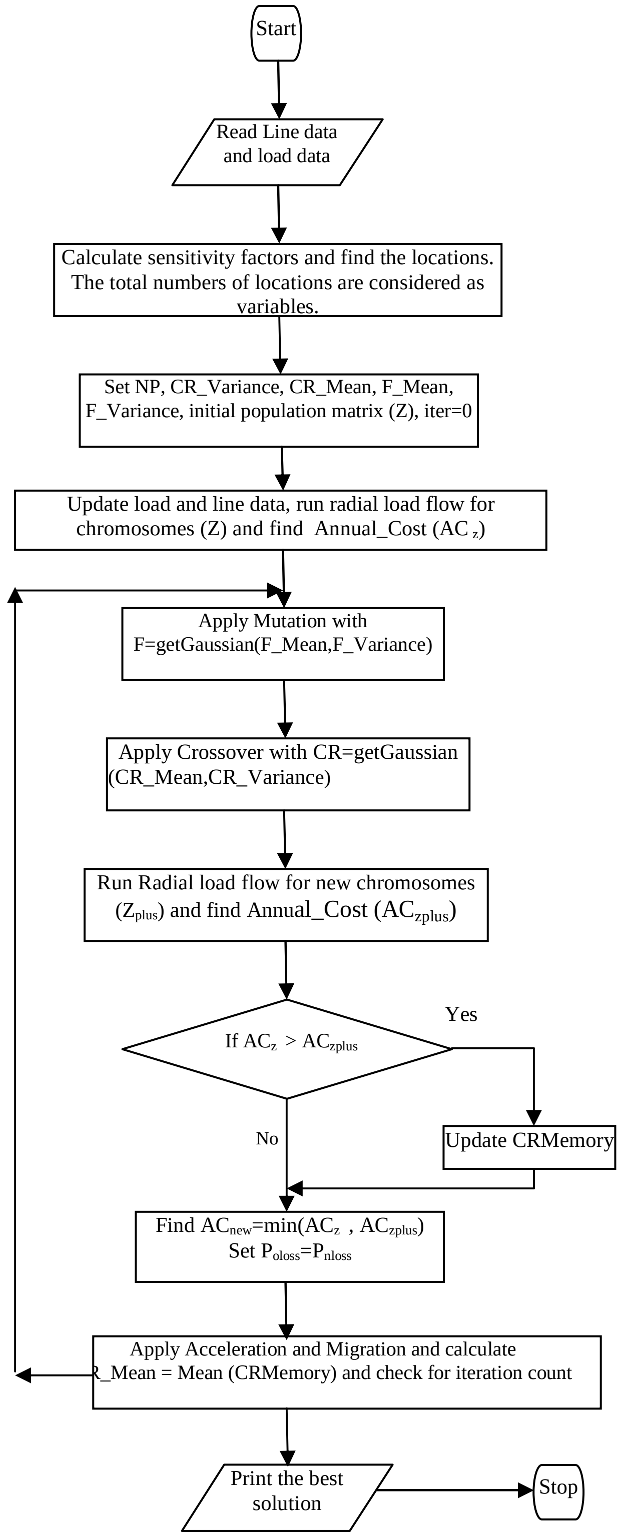

Figure 3: Flowchart for Reconfiguration through Hybrid SaHDE Algorithm

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5. SIMULATION RESULTS

The proposed algorithm has been programmed using J2EE servlet programming and run on a P-IV processor with 266 MHz personal computer. The effectiveness of the proposed algorithm has been tested on 10-bus, 34-bus and 85-bus radial distribution systems.

5.1 Test System 1

The Test System 1 is a balanced 10-bus radial distribution system [28] shown in figure 4, with the base of 23kV, served from single feeder. The load and line characteristic of the system is shown in table 1.

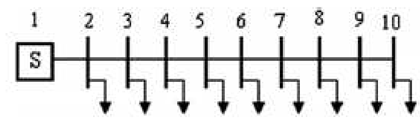

Figure 4: 10-Bus Radial Distribution System

Table 1: 10-Bus RDS Line and Load Data

Line No.	Start bus	End bus	R (Ω)	X (Ω)	P (kW)	Q (kVAR)
1	1	2	0.1233	0.4127	1840	460
2	2	3	0.0140	0.6057	980	340
3	3	4	0.7463	1.2060	1790	446
4	4	5	0.6984	0.6084	1598	1840
5	5	6	1.9831	1.7276	1610	600
6	6	7	0.9053	0.7886	780	110
7	7	8	2.0552	1.1640	1150	60
8	8	9	4.7953	2.7160	980	130
9	9	10	5.3434	3.0264	1640	200

With the help of sensitivity analysis the optimal locations were identified. The values of the loss sensitivity factor and normalized voltages are given in table 2.

Table 2: Initial Configuration Sensitivity Factors of 10-Bus RDS

Line No.	Start Bus	End Bus	Loss Sensitivity Factor(10^{-3})	Normalized voltage (|V| in pu / 0.95)
1	1	2	1.98	1.0451
2	2	3	0.20	1.0393
3	3	4	10.29	1.0141
4	4	5	8.64	0.9979
5	5	6	9.80	0.9654
6	6	7	2.08	0.9549
7	7	8	3.83	0.9357
8	8	9	8.11	0.9039
9	9	10	5.76	0.8816

From the table 2, it is clear that the normalized voltages at the buses from 5 to 10 are less than 1.01 pu. These buses are sequenced based on their sensitivity value. The first four buses such as 6, 5, 9 and 10, from the sequence have been considered as sensitive buses and needs voltage control. The FACTS devices are located on those locations to analyze the performance for optimization. The impact of the devices with respect to bus voltages and branch currents are shown in the table 3 and table 4 respectively. The tables reveal that the performance of the UPFC is better compared with the other two FACTS devices.

Table 3: Test System 1 Bus Voltages Without and With FACTS Devices

Bus No.	Without FACTS $\|V_{bus}\|$ (pu)	With SVC $\|V_{bus}\|$ (pu)	With TCSC $\|V_{bus}\|$ (pu)	With UPFC $\|V_{bus}\|$ (pu)
1	1.0	1.0	1.0	1.0
2	0.9929	0.9964	0.9961	0.9985
3	0.9873	0.9930	0.9953	0.9973
4	0.9634	0.9844	0.9810	0.9932
5	0.9480	0.9790	0.9810	0.9915
6	0.9171	0.9730	0.9690	0.9895
7	0.9071	0.9715	0.9598	0.9887
8	0.8889	0.9690	0.9429	0.9870
9	0.8586	0.9630	0.9164	0.9857
10	0.8374	0.9555	0.9000	0.9835

Table 4: Test System 1 Branch Currents Without and With FACTS Devices

Line No.	Without FACTS $\|I_{Line}\|$ (Amps)	With SVC $\|I_{Line}\|$ (Amps)	With TCSC $\|I_{Line}\|$ (Amps)	With UPFC $\|I_{Line}\|$ (Amps)
1	615.25	189.41	568.95	87.60
2	532.93	145.25	487.55	75.71
3	487.30	139.31	444.46	73.08
4	404.72	137.70	366.16	71.43
5	309.71	58.81	290.75	56.13
6	229.72	34.16	215.34	17.53
7	191.97	33.88	179.69	17.34
8	135.82	33.63	126.67	17.12
9	85.77	36.52	79.79	18.55

The power loss and annual operating cost of the distribution system with influence of capacitors and FACTS devices are compared in the table 5.

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Table 5: Comparison of Results with Capacitor Placement and FACTS Devices

Para meters	With out Comp ensat ors	With Capac itor Place ment [16]	With SVC	With TCSC	With UPFC
Power loss (kW)	783.77	704.883	55.28	671.27	18.96
Annual operating cost $/year	131,674	119,420	121,547	228,354	121,547
Min. Voltage in pu.	0.8374	0.9010	0.9555	0.9000	0.9835

From the table 5, the following observations were found,

i. Compared with static shunt capacitors, the loss reduction through the FACTS devices is better.
ii. Compared with static shunt capacitors, the minimum bus voltage is improved with SVC and UPFC.
iii. Compared with FACTS devices, the annual operating cost through the static shunt capacitors is reduced with small margin (it is obvious that the operating cost of the FACTS devices are more compared with static devices)
iv. Compared with SVC and TCSC, the performance of the UPFC is good.

5.2 Test System 2

The proposed method has been tested with 34-bus balanced radial distribution system [29], shown in figure 5.

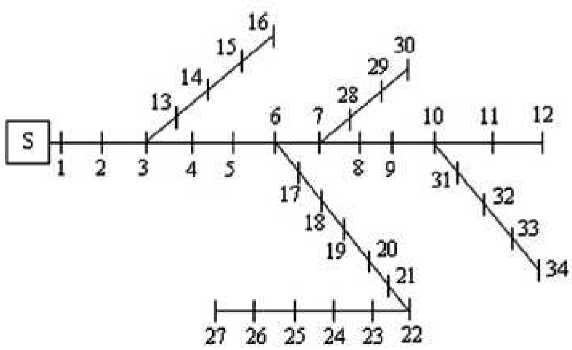

Figure 5: 34-Bus Radial Distribution System

As per the sensitivity analysis, the sensitive buses are identified. The constant K_p is assumed as the same value as followed for test system 1. For this test system, the lines 17, 20 and 18 are selected as optimal locations for the series voltage regulation and the buses 19, 22 and 20 are selected for reactive power injection/absorption. The proposed method reduces the power loss from 221.67kW to 81.32kW, and maintains the bus voltages well above minimum value. The optimal amount of reactance at the locations 17, 20 and 18, are -0.33 Ω, 0.06 Ω and -0.27 Ω respectively. The optimal amount of reactor at the buses is 1396kVAR, 728kVAR and 26kVAR respectively. The bus voltages with and without UPFC has been shown in the figure 6. It shows that bus voltages of the weaker buses 8, 9 and 10 are improved. The total operating cost of the distribution system is 56233.19$/year.

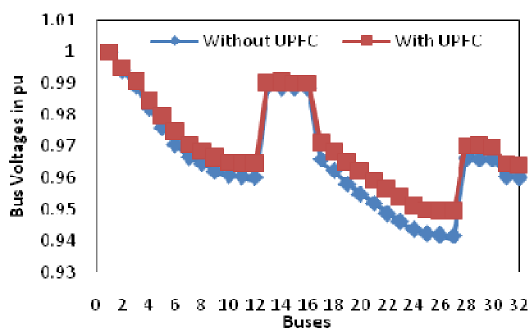

Figure 6: Bus voltages of Test System 2 With and Without UPFC

5.3 Test System 3

The proposed method has been validated further by implementing to 85-bus balanced radial distribution system [30], shown in figure. 7. The sensitive buses 8, 58 and 7 were identified through sensitivity analysis for reactive power injection/absorption. The associated lines for the series reactance locations are 16, 64 and 14. The constant K_p is assumed as the same value as followed for test system 1. With the use of SaHDE, the effective reactance has been identified for those buses. The power loss is reduced from 315.714kW to 95.36kW. The bus voltages with and without UPFC have been shown in the figure 8. The total operating cost of the distribution system is 72253.34$/year.

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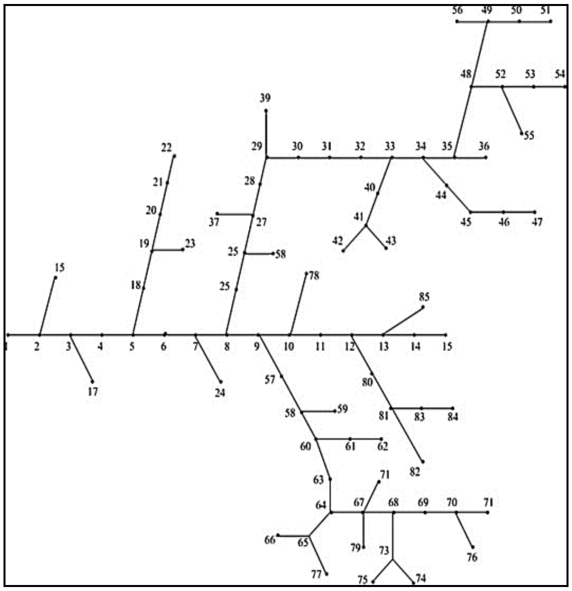

Figure 7: 85-Bus Radial Distribution System

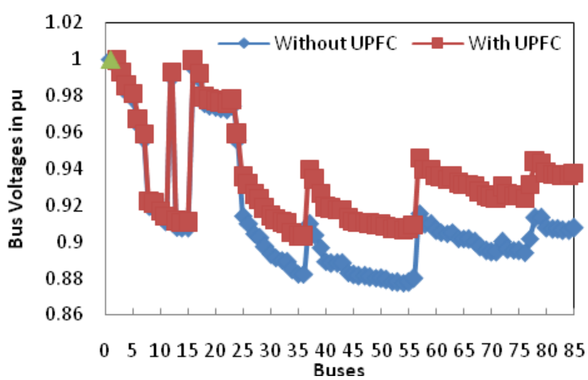

Figure 8: Bus Voltages of Test System 3 With and Without UPFC

6. CONCLUSION

In this paper, SaHDE algorithm along with sensitivity factors has been proposed to solve the reactive power control through FACTS devices. The purpose of the loss sensitivity factors is to identify the sensitive buses of the distribution system. With the integration of SaHDE, the optimal values of reactive power component generation/absorption by the FACTS devices at the identified locations were calculated. Furthermore, the suitability of the FACTS devices such as SVC, TCSC and UPFC were analyzed for distribution system optimization. From the results, it is absorbed that UPFC performs better in maintaining bus voltages above the minimum limit and the significant reduction of annual operating cost, compared with other FACTS devices. With the above observations, it is very well understood that the presence of UPFC in the distribution system greatly improves the efficiency. Besides, the improvements in the voltages at the buses provide opportunity for expansion planning and protection during faulted conditions. The main advantages of the proposed algorithm with the previous works addressed are that, evade of heavy numerical computing, promising the global optimum, solution for the control parameters, quick searching for optimal solution and suitable for dynamic load patterns.

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