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VOLTAGE VANGUARD: GAMS-DRIVEN SOLUTIONS FOR OPTIMIZING CAPACITOR LOCATION AND SIZING IN RURAL ENERGY NETWORKS

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Abstract: The need for reducing active power loss in radial distribution systems (RDS) has become paramount as global power consumption continues to rise. This paper presents a new approach using the Generalized Algebraic Modeling Systems (GAMS) software to find the optimal location and sizing of capacitors in RDS. The approach converts the problem into a mixed integer nonlinear program (MINLP) and solves it using MINLP-SBB Solver. The effectiveness of the approach is demonstrated by testing it on an IEEE 10 bus RDS and comparing the results with other optimization techniques. The approach is found to be both efficient and accurate, providing better results in less execution time. The proposed method significantly reduces power loss, enhances the voltage profile, improves power factor, and ultimately enhances system stability, making it safer to operate. The paper provides a detailed explanation of the problem formulation and necessary mathematical models required to describe the system. The approach has broad applications in the power sector, and its use will result in significant energy savings, making it an essential tool for power system engineers and researchers.

Keywords: radial distribution system, power loss reduction, capacitors, GAMS, optimization, system stability.

1. Introduction

The power consumption is increasing at the distribution side day by day (Arya et al., 2019). Also, it is estimated that 13% of the total generated power is lost as I^2R loss in the distribution level (Devabalaji et al., 2015). With the different types of loads present in Radial Distribution System(RDS), there are various problems like uneven voltage profile, poor power factor, high power losses, energy losses, poor system stability, power quality issues etc. affects the system. The injection of volt-ampere reactive's (VARs) into the distribution system will also affect the system but there are some advantages too. The Shunt Capacitor banks are mostly installed in the distribution lines to inject the VARs there by the system voltage profile and power factor is enhanced. The main problem is to identify capacitor's best location and proper size. There are many ways of solving the capacitor placement and sizing problem. Many methods and algorithms have been proposed by many researchers to solve this problem.

In Srinivasas Rao et al. (2011), the best location of capacitor can be found calculating the Loss sensitivity factors at the buses and Plant Growth Simulation Algorithm (PGSA) is employed to calculate of capacitors size optimally at the optimally selected buses. In Devabalaji et al. (2015), optimal location of capacitor banks can be found by Loss Sensitivity Factor (LSF) and Voltage

Stability Index (VSI) and Bacterial Foraging optimization algorithm (BFOA) is used to estimate the optimal capacitor banks size.

In Prakash et al. (2007), Capacitor Placement is done by Loss Sensitivity Factors and its Sizing is done by employing Particle Swarm Optimization (PSO) technique. In Su et al. (1996), a Fuzzy reasoning is applied to optimally locate the capacitor in radial distribution system and size of the capacitors is considered continuous.

In this paper, optimal location and sizing of capacitor banks in a radial distribution system will be solved by using the General Algebraic Modeling System (GAMS) Software. The no. of capacitors to be placed can be varied, the proposed method will locate the optimal locations and suggest the optimal size accordingly. The problem is written in Mixed Integer Nonlinear Programming (MINLP) form, and it is coded in the GAMS programming language. With the obtained location and sizes, the values are substituted in Load flow program and are run in MATLAB R2020b. The various parameters such as Voltage profile, Voltage Profile Index (VPI), etc. are calculated and the results are compared with the results of other optimization techniques.

2. Problem Formulation

2.1 Objective: The main aim of this paper is to minimize the active power loss in the givenRDS by positioning and sizing of thecapacitor using GAMS.

The objectives of this paper are to:

1. Calculate the total active power loss (KW) and minimize them.
2. Find the Capacitors best location and their size for the desired no of capacitors.
3. Calculate the % Loss Reduction.
4. Calculate the Loss Saving (KW).
5. Calculate the Annual Energy Saving (KWh).

*2.2Objective Function:*The Objective function is the total active power loss. The total active powerloss function is givenby: From the above (1), the PT,LOSSis a function with the dependent variables V(i), δ(i) and C(i). Where, V(i) is the Voltage atthebus i, δ(i) is the power angle at the bus i and $Q_C(i)$ is the reactive power compensated at bus i

*2.3 Mathematical Models:*The Mathematical Model will give a clear idea of the given distribution networkstatus. The Model canbe described by set of equations and which reflects thesystemcharacteristics. The equations required for describing the system areasfollows:

Transmission line model:Consider a transmission line between the two buses*i* and *j* as shown in Figure 1 (Saadat H., 2010). Let I_{ij}be the line current between the nodes *i*.

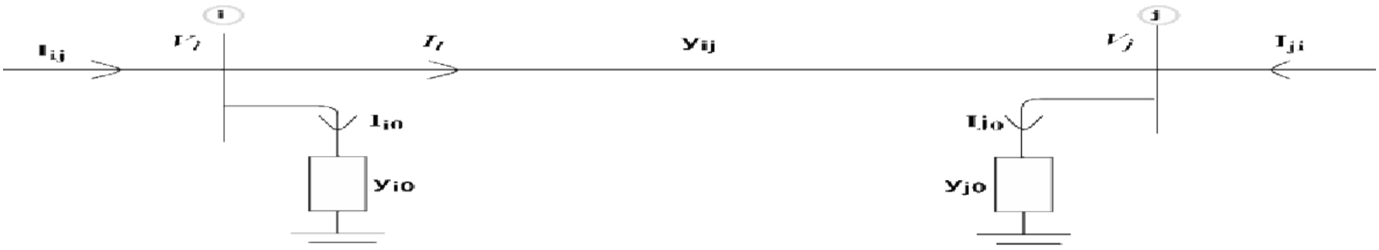

Figure. 1. Transmission line model for calculating the power loss.

and *j* and the complex power flows from bus *i* to *j* is

$S_{ij}= V_i I_{ij}^*$ (2)

and from bus *j* to *i* is

$S_{ji} = V_j I_{ji}^*$ (3)

The total power loss in i-j is equal to the sum of power flows obtained from (2) and(3), i.e.,

$$SL_{ij} = S_{ij} + S_{ji} \quad (4)$$

The total active power loss can be given by

$$P_{T,LOSS} = \text{Real part}[\sum_i \sum_j S(L_{ij})]; \ \forall \ i \neq j \quad (5)$$

The Equation (5) is the main equation for calculating the power loss, which is simplified (Srinivasas Rao et al., 2011; Mohsin, 2016) and written in the GAMS program.

Capacitor: The shunt capacitors will inject the vars into the system. The shunt capacitors can be a fixed or switchable or both. The active power compensated at each bus is within the range of $[Q_{Cmin} Q_{Cmax}]$. The capacitors sizes are discrete with in the standard range.

The reactive power compensated at bus *i* is limited to (Srinivasas Rao et al., 2011):

$$Q_C(i) \leq \sum_{i=1}^{n} Q_d(i) \quad (6)$$

The total reactive power compensated in the given bus system is limited to:

$$\sum_{i=1}^{n} Q_d(i) \leq \sum_{i=1}^{n} Q_d(i) \quad (7)$$

2.4 Power Balance Equations: The power balance equations, which characterize the power flow throughout the power system is given below (Stevenson et al., 1994; Kothari et al., 2003):

$$P_g(i) - P_d(i) - \sum_{i=1}^{N} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} + \delta_i + \delta_i) = 0 \quad (8)$$

$$Q_g(i) - Q_c(i) - Q_d(i) + \sum_{i=1}^{N} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} + \delta_i + \delta_i) = 0 \quad (9)$$

$\forall$, i=1, 2. ......, N

where

$|V_{ij}|$ is the voltage magnitude at bus i,

$|Y_{jj}|$ is magnitude of the admittance between buses i and j, δ_{ij} is angle of the admittance between buses i and j, $P_d(i)$ is the active load power in bus i,

$Q_d(i)$ is the reactive load power in bus i,

$Q_C(i)$ is the reactive power compensated at bus i, $P_g(i)$ is the active power generated at bus i, $Q_g(i)$ is the reactive power generated at bus i and N is equal to total no. of buses in the given system.

2.5 Operational Constraints:

Voltage and Stability limits: The voltage magnitude at each bus should be kept inthe range of:

$$V\min \leq |V_i| \leq V\max$$

The stability angle (δ) at each bus should be kept in the range of: (10)

$$\delta\min \leq |\delta_i| \leq \delta\max \quad (11)$$

Capacity & No. Of Capacitor banks Constraints: The Capacitor Constraint of the capacity can be expressed as:

$$Qc\min(\,)*iUC(\,)i \leq Qc\min(\,)i \leq Qc\max(\,)*i \qquad UC(\,)i \quad (12)$$

No. of Capacitors banks constraint is formulated as:

$$N \qquad \sum U_C(\,)i \leq N \quad (13)$$

i=1 Where, $U_C(\,)i$ is a binary variable i.e.

1, if capacitor at bus i placed

$U^C(\,)i \leq$ (14)

0, otherwise

2.6 Parameters Calculations

Voltage Profile Index (VPI): For a better operation of a power system network, there should be a better voltage profile, for that the voltage profile index should be minimum (Arya et al., 2019). In other words, if the VPI at each bus is nearer to zero, then the capacitor is said to be placed in the best location and the system is running in safe mode. The VPI at bus i is calculated by:

$$VPI(\,)i = \square\square\square V^{ref}V - refV(\,)i \; \square\square\square\square 2 \quad (15)$$

Where, V_{ref} is the reference voltage and $V(i)$ is the Voltage at the i^{th} bus.

Loss Saving (KW):Loss Saving (KW) is calculated as:

Loss Saving = {Power Loss due to Uncompensated Case} - {Power Loss due to placement of Capacitor} (16)

%Loss reduction: % Loss reduction = (Loss saving/(Power loss due to uncompensated case))*100 (17)

Total Annual Energy Saving (kWh)(Arya et al., 2019)*:n*

$$Total\ Annual\ Energy\ Saving = \sum (Loss\ saving) * 8760 \quad (18)$$

i=1 n = No. of Months

3. Problem Simulation

In this section, an introduction to GAMS software and the steps involved during problem simulation is discussed.

3.1 *General Algebraic Modeling System (GAMS):* The General Algebraic Modeling System (GAMS) is a modeling tool for mathematical programming and optimization purpose (GAMS Documentation Center, 2021; Brooke et al., 1998; Soroudi, 2017). The structure of GAMS is shown in Figure 2. The program is written in input file with a proper solver and the program is compiled, the output can be seen in listing file.

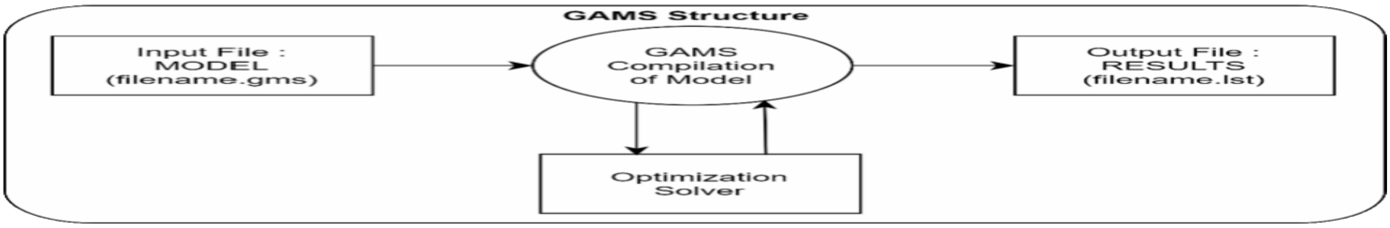

Figure2. GAMS Structure.

Linear programming (LP), mixed integer programming (MIP), nonlinear programming (NLP), quadratic constrained programming (QCP), mixed integer non-linear programming (MINLP), and multi objective optimization problems can be modeled in GAMS. The main advantages of GAMS are Easy to implement, Portable & Transferable and Adoptable to new technical updates because of inclusion of new algorithms. In this paper, the problem is written in a mixed integer nonlinear programming (MINLP) form and an MINLP solver named SBB (GAMS Documentation Center, 2021; Brooke et al., 1998) is used.

3.2 Procedural Steps:

*Uncompensated Case:*Uncompensated Case (or) Base Case means the distribution system without any capacitors installed. The steps involved in this case are:

1. Load the Line & Bus Data of the given distribution system.
2. Run Load flow program in MATLAB.
3. Calculate total active power loss (KW) in the given distribution system.

*Compensated Case:*On contrary the Compensated Case refers to the distribution system with capacitors installed, no. of capacitors is to be decided based on various factors. The no. of capacitors to be placed can be affected by their installing and maintenancecosts. The steps involved in finding the optimal location and size of the capacitor in the given RDS using the GAMS approach areas follows:

1. Declare Sets, Parameters, Tables, Variables, Scalars and Binary Variable etc. in theGAMS.
2. Write the Equations, which are mentioned in Section 2, in GAMS programming (Soroudi, 2017; Oscar Danilo Montoya et al., 2020) correctly.
3. Run the GAMS program.
4. Obtain the optimal location and sizes of capacitors, for required no. of capacitor.
5. With the Obtained capacitor location and size, use them in Load flow program inMATLAB as the $Q_{injection}$.
6. Calculate the total active power loss (KW), the parameters mentioned in section2.6 and compare them with the results of uncompensated case and other techniques.

4 Case Study

4.1 *Test Case: IEEE 10 Bus System:*An IEEE 10 Bus, radial distribution system (RDS) (Srinivasas Rao R., Narasimham S.V.L., Ramalingaraju M., 2011; Baghzouz Y., 1990) is considered as a testcase in this paper and its one- line diagram is show in Figure 3.

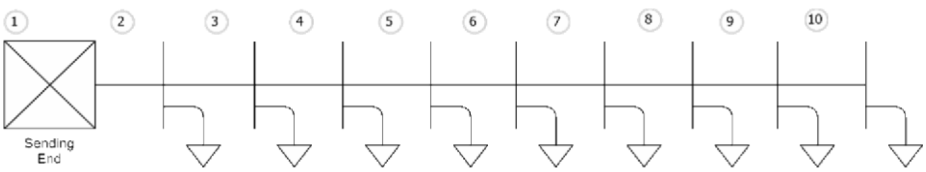

Figure3. One-line diagram of IEEE 10 bus RDS.

Table 1. The Line data and Load data of IEEE 10 bus RDS (Srinivasas Rao et al., 2011).

Line No.	From Bus i	to Bus i+1	*Ri*, i+1 (Ω)	*Xi*, i+1 (Ω)	P_L kW	Q_L kVAR
1	1	2	0.1233	0.4127	1840	460
2	2	3	0.0140	0.6057	980	340
3	3	4	0.7463	1.2050	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	1.1640	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

The line data and load data for the above IEEE 10 bus RDS is given in theTable1 (Srinivasas Rao et al., 2011). The proposed GAMS based approach is tested on this IEEE 10 bus RDS test case.

4.2 *Result and Discussion:* Using GAMS programming the no. of capacitor banks to be placed can also be varied, Figure 4 shows the plot between different no. of capacitors and the respective power loss. For the uncompensated case, the total active power loss obtained is 783.766 kW. From Figure 4, it is observed that with the increase in no. of capacitor banks installation the power loss is saturated to a low value while compare with the initial uncompensated value. As the no. of capacitor banks increases the installation and maintenance cost corresponding will also increases. So, the best possible no. of capacitor banks which will obey the demand of minimum loss and minimum costs are 3, 4 and 5. Among them the 4 capacitor banks is the best to consider. In this paper, 4 no. of capacitors are to be placed optimally with optimal sizes using GAMS. Table 2 shows the 4 capacitor banks location and size obtained by GAMS.

The compensated case in this paper has 4 capacitor banks which are placed and sized optimally in the IEEE 10 bus RDS by GAMS. Voltage profile plot for uncompensated and compensated case is as shown in Figure 5. It is observed that by placing the capacitors by using GAMS the voltage profile at each bus is enhanced while compared with voltage profiles of the uncompensated case. The Voltage Profile Index plot for the uncompensated and compensated case is as shown in Figure 6. The voltage profile index(VPI) should be closer to zero, which will ensure the safe operation of the system(Arya et al., 2019). From Figure 6, it is observed that the VPI at each bus is low for the compensated case and large for the uncompensated case.

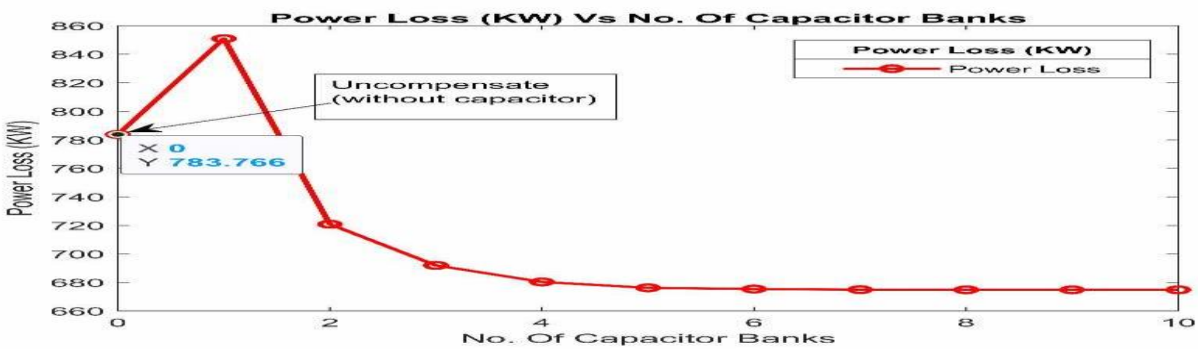

Figure 4. Power Loss (KW) Vs No. Of Capacitor Banks.

Table 2. Location and Sizes for 4 no. of capacitor banks using GAMS.

Location (At bus)	Size (KVAR)
3	4050
5	3443
6	1460
10	610

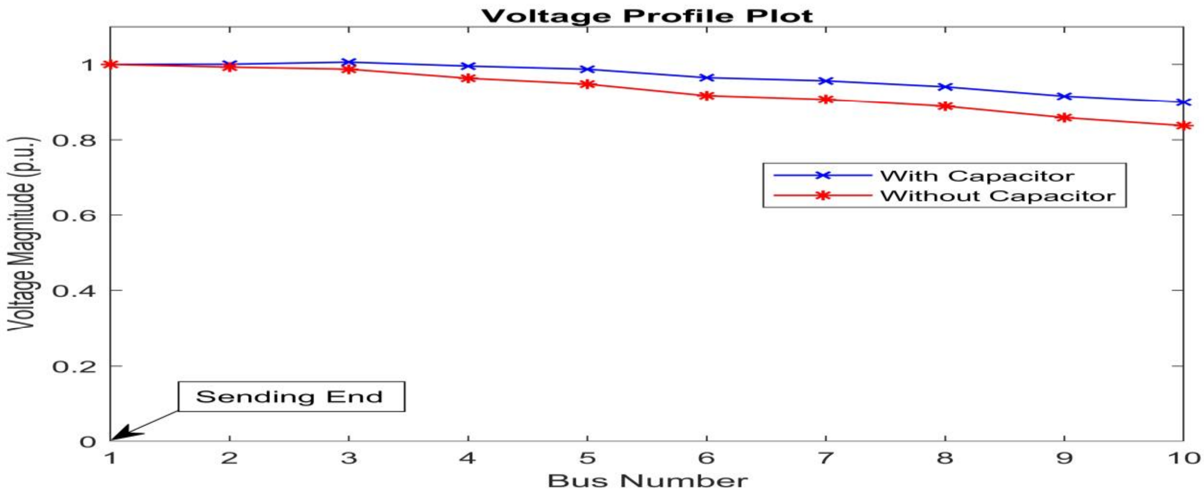

Figure 5. Voltage ProfilePlot: with & without Capacitor for 10 bus system

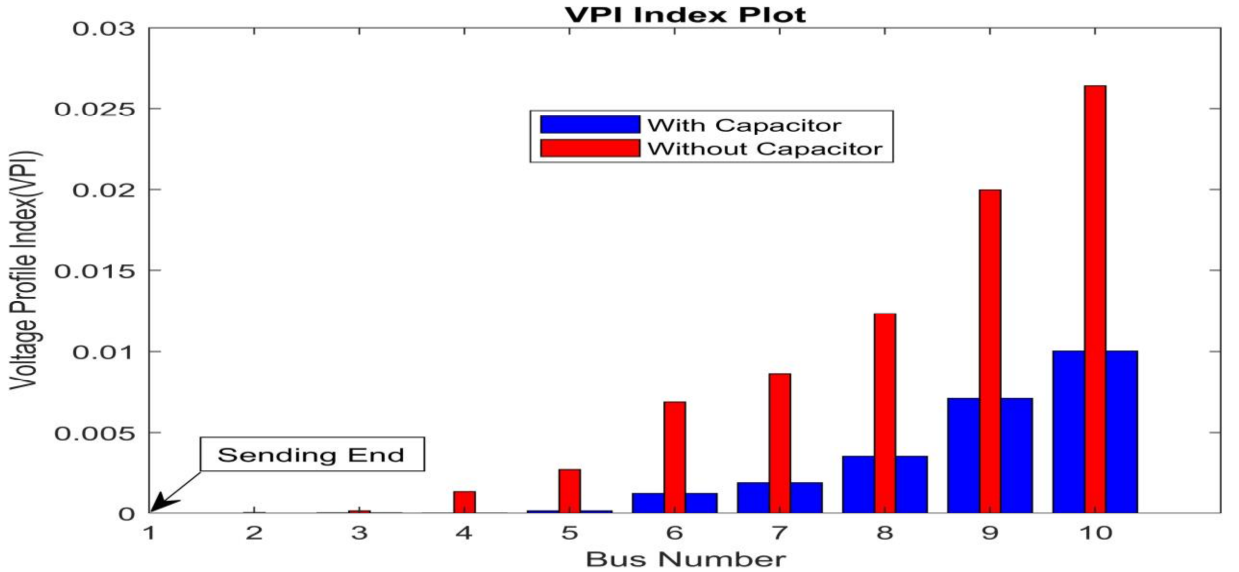

Figure 6. VPI plot: with & without Capacitor for 10 bus system.

Table 3. Simulation Results of IEEE 10 Bus RDS, and comparison of results with other methods.

	Base Case	Comparison of optimization techniques with the proposed GAMS method			
		The Proposed Method using GAMS	Plant Growth Simulation	PSO (Prakash et al., 2007)	Fuzzy Reasoning (Su et al., 1996)

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			(Srinivas Rao et al., 2011)		
Location & Size	-	At Bus KVAR 3 4050 5 3443 6 1460 10 610	At Bus KVAR 6 1200 5 1200 9 200 10 407	At Bus KVAR 6 1174 5 1182 9 264 10 566	At Bus KVAR 4 1050 5 1050 6 1950 10 900
Power Loss (kW)	783.77	680.33	694.93	696.21	704.883
%Loss reduction	-	13.2	11.33	11.17	10.065
Loss Saving (kW)	-	103.44	88.84	87.56	78.8870
Annual energy saving (kWh)	-	906134.39	778238.40	767025.59	691050.12

Table 4. Parameters and Values.

Parameter	Value
N	10
V_{ref}	1.0 p.u.
[*V*min *υ*max]	[0.91.1] p.u.
[δminδmax]	[-3.1416+3.1416]rads
[*Q*cmin *Q*cmax]	[1504050]KVARs

By using GAMS approach, the capacitors of sizes 4050, 3443, 1460 and 610 KVARsare placed at locations 3, 5, 6 and 10 buses respectively. With uncompensated case in the above IEEE 10 bus RDS, the total active power loss is 783.766 KW and it is reduced to 680.33 KW after placing the 4 capacitors using GAMS approach. In Table 3the obtained results by the proposed approach are compared with PGSA(Srinivasas Rao R., Narasimham S.V.L., Ramalingaraju M., 2011), PSO (Prakash K., Sydulu M., 2007)and Fuzzy reasoning (Su C.T, Tsai C.C., 1996) results. From Table 3, it seems that by the proposed approach the total active power loss is 680.33 KW, % Loss reduction is 13%, Loss saving is 103.44 KW and the annual energy savings is 906134.39KWh and these arebetter compared with the other methods.

5. Conclusion

As the capacitor in the distribution system supply reactive power which will reduces the active power loss and improves system voltage profile, the appropriate placement and proper size of capacitors are needed. With the GAMS approach, the problem of finding the optimal location and size become easy and simple. The results seem quite better compare with the results obtained by other techniques. This proposed GAMS approach can be extended to large no. of bus system and also to mesh type distribution system.

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