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Optimal Placement of Capacitor and Sizing in a Radial Distribution Network to Reduce Real Power Losses

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Abstract: ***Electricity distribution constitutes the concluding stage in the delivery of electricity to the consumers. This distribution network transports electricity from the transmission system and delivers it to the consumers. The distribution network includes medium-voltage power lines, substations and pole-mounted distribution transformers, open and close switches, low-voltage distribution wiring and measuring meters. Distribution circuits are fed from a transformer located in an electrical substation, where the voltage is reduced from the high values used for power transmission. A radial distribution network leaves the station and passes through the network area with no normal connection to any other supply. In this paper, identification of the ideal spots to place the capacitors in the radial distribution network and the kVAr rating (Size) of those capacitors is done. This is done to reduce the Annual cost incurred due to I^2R loss in the system and for installing capacitor bank. This project aims to achieve the same by gaining the advantage of applying one of the Artificial Intelligence techniques called genetic algorithm based on real coding and binary coding. The effectiveness of this proposed method was tested on an IEEE 34-bus test utility system and the results were compared with the available literatures.***

Keywords: 34 Bus RDS, Genetic Algorithm, Binary and Real Encoding, Radial Distribution System (RDS), Reactive Power, Real Power Losses, Voltage Magnitude

Nomenclature

V_j = Voltage magnitude of the j^{th} bus
P_j = Real power injection at the jth bus
Q_j = Reactive power injection at the j^{th} bus
δ_j = Phase angle at the j^{th} bus
P_{acc} = Real power accumulated
Q_{acc} = Reactive power accumulated
$P_{ij(loss)}$ = Real power loss in the line connecting i^{th} and j^{th} bus
NVB = Number of buses that violate the recommended voltage limits
V_L = Upper limit of the i^{th} load bus
V_i = Voltage magnitude of bus i
V_{min} = Minimum Voltage Limit
V_{max} = Maximum Voltage Limit
P_i = Real power load demand in the bus i
Q_i = Reactive power load demand in the bus i
R_{ij} = Resistance in the line connecting the i^{th} and j^{th} bus
VDI = Voltage Deviation Index

1. Introduction

Until recently many researchers have shown interest in reducing the losses in radial distribution system by optimal capacitor placement and sizing. They tried several different load flow methods and A.I techniques over the years. Their findings and suggestions are reviewed here:

[1]Sneha Sultana, Provas Kumar Roy presented a teaching learning based optimization (TLBO) approach to minimize power loss and energy cost by optimal placement of capacitors in radial distribution systems. Teaching learning based optimization (TLBO) is a new variant of meta-heuristic optimization technique inspired by the natural phenomenon of teaching and learning process. In this optimization technique, a group of students in a class is considered as a population and the solution vector of the objective is analogous to the grade point of different subjects offered to the students. The result of a student is analogous to fitness function in other population-based techniques, to represent the quality of each solution set. TLBO is based on the concept of teaching–learning process in a class.To check the feasibility, the proposed method was applied on standard 22, 69, 85 and 141 bus radial distribution systems. The authors compared the performance of their proposed TLBO technique with other methods like GA, PSO, Fuzzy GA and DSA. The comparison results confirmed the effectiveness and the superiority of their proposed TLBO approach over the other A.I techniques.**[4]S.P. Singh, A.R. Rao** presented a particle swarm optimization (PSO) approach for finding the optimal size and location of capacitors .Their proposed technique found optimal locations for shunt capacitors from the daily load curve. In addition, it determined the suitable values of fixed and switched capacitors. Particle swarm optimization (PSO) is an evolutionary technique developed from researches on swarm such as fish schooling and bird flocking. This method is capable of handling continuous state variables easily and search a solution space effectively. A dynamic sensitivity analysis method was used to select the candidate installation locations of the capacitors to reduce the search space of this problem. A simple iterative method is used to compute the power flow. To check the feasibility, the proposed method was applied on 70-bus and 135-bus systems. The authors then compared with their solutions with those obtained by Tabu Search (TS), Hybrid and Genetic Algorithms. The results obtained after comparison demonstrated that their proposed PSO approach offered the global optimal solution with greater saving.**[11]R. Srinivasas Rao, S.V.L. Narasimham, M. Ramalingaraju** presented a new and efficient approach for capacitor placement in radial distribution systems that determine the optimal locations and size of capacitor with an objective of improving the voltage profile and reduction of the power losses. The Plant Growth Simulation Algorithm is based on the plant growth process, where a plant grows a trunk from its root; some branches will grow from the nodes on the trunk; and then some new branches will grow from the nodes on the branches. Such process is repeated, until a plant is formed. Based on an analogy with the plant growth process, an algorithm can be specified where the system to be optimized first ''grows'' beginning at the root of a plant and then ''grows'' branches continually until the optimal solution is found. To check the feasibility, the proposed method was applied on 10, 34, and 85-bus radial distribution systems. The solutions obtained by the proposed method were compared with other heuristic and PSO methods. The comparison proved that the proposed method placed capacitors at less number of locations with optimum size and offered much net annual saving in initial investment.**[15]D. Das** presented a genetic algorithm (GA) based fuzzy multi-objective approach for determining the optimum values of fixed and switched shunt capacitors to improve the voltage profile and maximize the net savings in a radial distribution system. The two objectives, i.e. maximization of net savings and minimization of the nodes voltage deviation were first fuzzified and, then, dealt with by integrating them into a fuzzy satisfaction objective function through appropriate weighting factors. The optimization technique of the Fuzzy GA was then adopted to solve the fuzzy multi-objective problem for obtaining the optimum values of shunt capacitors. The simulation on a medium size distribution network has proved the feasibility of the proposed approach and the obtained results are quite good and they encourage the implementation of the proposed strategy on a large size distribution network.

2. Load Flow

To meet the present emerging domestic, industrial and commercial load day by day, effective forecasting of the RDS is essential. To ensure the effective planning with load transferring, the load flow study of RDS becomes utmost significant. Load flow analysis is concerned with describing the operating state of an entire power system. Newton Raphson and Fast decoupled load flow solution techniques are used to solve well- behaved power system. However these are in general unsuitable for solving load flow for RDS because of their low X/R ratios of branches.

A section of RDS has a sending end bus (i^{th} bus) and receiving end bus (j^{th} bus). The line in connection with these two sections has impedance ($Z = r + jx$). The power flow through this line can be in both directions. The power flow at the sending end bus($S_i = P_i + jQ_i$)is different from the power flow at the receiving end bus$\left(S_j = P_j + jQ_j\right)$.

A load flow algorithm [13] solves the power balance equations at all buses and finds the corresponding voltage solution. At load buses, the load flow algorithm will solve for the bus voltage magnitude and phase angle. The known parameters at a load bus are the received real and reactive powers. Hence a load flow must solve for the bus voltage magnitude in (1) and phase angle, (2).

$$V_j^2 = -\left[rP_j + xQ_j - \frac{V_i^2}{2}\right] + \sqrt{\left(rP_j + xQ_j - \frac{V_i^2}{2}\right)^2 - [r^2 + x^2][P_j^2 + Q_j^2]} \quad (1)$$

$$\delta_j = \delta_i - \sin^{-1}\left(\frac{xP_j - rQ_j}{V_i V_j}\right) \quad (2)$$

If the voltage magnitude and phase angle values are to be computed for the receiving end bus, the only variables needed are the receiving end bus real and reactive power values, the sending end bus voltage magnitude and phase angle value, and the value of the line impedance connecting the two buses. All the values needed for the load bus calculations are easily attainable in practice.

2.1 Load Flow Algorithmic steps

Step 1 : Read System data structure.$Q_{T,loss} = \sum_{i=1}^{n} Q_{ij(loss)}$
Step 2 : Goto Slack bus.
Step 3 : Initialize $P_{acc} = 0$ and $Q_{acc} = 0$
Step 4 : Calculate P and Q for all buses
Step 5 : CalculateV_j and $\delta_j$for all buses using equations (1) and (2)
Step 6 : DetermineP_{loss} and $Q_{loss}$for all lines
Step 7 : Update P_{acc} and Q_{acc}using the formula
$P_{acc} = P_{loss} + P_j$; $Q_{acc} = Q_{loss} + Q_j$
Step 8 : Goto Next bus and reprise the step from 4 to 8 up until Last bus is reached.
Step 9 : Check for convergence, (3) and print the result, else goto step 2.

2.1.1 Convergence Criteria

In this Load Flow, it is checked whether the sum of powers flowing out of the lines connected to each bus equals (or equals within a tolerable limit) the net power injected into that bus. Mathematically, convergence criteria for the presented load flow is given in (3)

$$(PG_i - PD_i) - \left[\sum_j \left(V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij})\right)\right] \le \varepsilon$$

$$(QG_i - QD_i) - \left[\sum_j \left(V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij})\right)\right] \le \varepsilon \quad (3)$$

3. Mathematical Problem Statement

3.1 Total Real and Reactive power loss

The real & reactive power loss in the line connecting i^{th} and j^{th} bus is given by,

$$P_{ij(loss)} = \frac{[P_j]^2 + [Q_j]^2}{[V_i]^2} * R_{ij} \quad (4)$$

$$Q_{ij(loss)} = \frac{[P_j]^2 + [Q_j]^2}{[V_i]^2} * X_{ij} \quad (5)$$

The Total real& reactive power loss of RDS having 'n' buses and 'n-1' branches is given by,

$$P_{T,loss} = \sum_{i=1}^{n} P_{ij(loss)} \quad (6)$$

$$Q_{T,loss} = \sum_{i=1}^{n} Q_{ij(loss)} \quad (7)$$

3.2 Voltage Deviation Index (VDI)

The Voltage Deviation Index is calculated using the formula,

$$\mathrm{VDI} = \sqrt{\frac{\sum_{i=1}^{NVB}(V_{Li}-V_L)^2}{N}} \quad (8)$$

To enumerate the degree of violation of limits imposed on voltages at buses in a RDS, VDI is well-defined where NVB is the number of buses that violate the recommended voltage limits and V_L is the upper limit of the i^{th} load bus. In the course of reconfiguration, if the state of the system has voltage limit violations, the anticipated solution must try and lessen the index VDI. When a branch is switched on and another is switched out in a loop, the solution space is no longer continuous. The variable that defines the status of a branch as to whether it is switched in/out adopts discrete states of zero or one. Owing to the discontinuous and discrete nature of the problem, classical techniques are rendered inappropriate and the practice of global search techniques is essential.

3.3Objective function for network reconfiguration in RDS

The objective is to minimize the I^2R losses in RDS and thereby the voltage profile of the system is enhanced. This is attained by finding out the best set of branches to be switched out such that the subsequent RDS experiences least I^2R loss and has the best voltage profile.

The mathematical model of the problem can be expressed by the following expression.

$$\text{Minimize } f = \sum_{i=1}^{n} P_{ij(loss)} + \sqrt{\frac{\sum_{i=1}^{NVB}(V_{Li}-V_L)^2}{N}} \quad (9)$$

Subject to,

$$V_{min} \leq |V_i| \leq V_{max}$$

The first term in the (9) represents the total I^2R loss in the system and the second term denotes voltage deviation index (VDI).

4. Genetic Algorithm

4.1 Introduction

Genetic algorithms are a part of evolutionary computing, which is a rapidly growing area of artificial intelligence.

1.1.1 Chromosome

All living organisms consist of cells. In each cell there is the same set of chromosomes. Chromosomes are strings of DNA and serves as a model for the whole organism. A chromosome consists of genes, blocks of DNA. Complete set of genetic material (all chromosomes) is called genome. Particular set of genes in genome is called genotype. The genotype is with later development after birth base for the organism's phenotype, its physical and mental characteristics, such as eye colour, intelligence etc.

4.1.2 Reproduction

During reproduction, first occurs recombination (or crossover). Genes from parents form in some way the whole new chromosome. The new created offspring can then be mutated. Mutation means, that the elements of DNA are a bit changed. This changes are mainly caused by errors in copying genes from parents. The fitnessof an organism is measured by success of the organism in its life.

4.1.3 Search Space

The space of all feasible solutions is called search space (also state space). Each point in the search space represents one feasible solution. Each feasible solution can be "marked" by its value or fitness for the problem.

4.2 Outline of Steps Involved In GA

1. **[Start]** Generate random population of n chromosomes (suitable solutions for the problem)
2. **[Fitness]** Evaluate the fitness f(x) of each chromosome x in the population
3. **[New population]** Create a new population by repeating following steps until the new population is complete
1. **[Selection]** Select two parent chromosomes from a population according to their fitness (the better fitness, the bigger chance to be selected)
2. **[Crossover]** With a crossover probability cross over the parents to form a new offspring (children). If no crossover was performed, offspring is an exact copy of parents.
3. **[Mutation]** With a mutation probability mutate new offspring at each locus (position in chromosome).
4. **[Accepting]** Place new offspring in a new population
4. **[Replace]** Use new generated population for a further run of algorithm
5. **[Test]** If the end condition is satisfied, **stop**, and return the best solution in current population
6. **[Loop]** Go to step 2

4.3 Selection

4.3.1 Roulette Wheel Selection

Parents are selected according to their fitness. The better the chromosomes are, the more chances to be selected they have. Imagine a roulette wheel where are placed all chromosomes in the population, everything has its place big accordingly to its fitness function, like on the following picture.

4.3.2 Rank Selection

The previous selection will have problems when the fitness differs very much. For example, if the best chromosome fitness is 90% of all the roulette wheel then the other chromosomes will have very few chances to be selected. Rank selection first ranks the population and then every chromosome receives fitness from this ranking. The worst will have fitness **1**, second worst **2** etc. and the best will have fitness **N** (number of chromosomes in population). After this all the chromosomes have a chance to be selected. But this

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method can lead to slower convergence, because the best chromosomes do not differ so much from other ones.

4.4 Encoding

4.4.1 Binary Encoding

Binary encoding is the most common, mainly because first works about GA used this type of encoding. In binary encoding every chromosome is a string of bits, 0 or 1.

Chromosome A	101100101100101011100101
Chromosome B	111111100000110000011111

4.4.2 Real Encoding

Direct value encoding can be used in problems, where some complicated values, such as real numbers, are used. Use of binary encoding for this type of problems would be very difficult. In real encoding, every chromosome is a string of some values. Values can be anything connected to problem, form numbers, real numbers or chars to some complicated objects.

Chromosome A	1.2324 5.3243 0.4556 2.3293 2.4545
Chromosome B	ABDJEIFJDHDIERJFDLDFLFEGT

4.5 Crossover and Mutation

4.5.1 Binary Encoding

4.5.1.1 Crossover

Single point crossover - one crossover point is selected, binary string from beginning of chromosome to the crossover point is copied from one parent, and the rest is copied from the second parent
11001011+11011**111** = **11001111**

Two point crossover - two crossover point are selected, binary string from beginning of chromosome to the first crossover point is copied from one parent, the part from the first to the second crossover point is copied from the second parent and the rest is copied from the first parent
110010**11** + 11**0111**11 = **11011111**

Uniform crossover - bits are randomly copied from the first or from the second parent
1**10**010**11** + **11**0**111**01 = 11011111

Arithmetic crossover - some arithmetic operation is performed to make a new offspring
11001011 + 11011111 = 11001001 (AND)

4.5.1.2 Mutation

Bit inversion - selected bits are inverted
1**1**001001 => 1**0**001001

4.5.2 Real Encoding

4.5.2.1 Crossover

All crossovers from binary encoding can be used

4.5.2.2 Mutation

Adding a small number (for real value encoding) - to selected values is added (or subtracted) a small number
(1.29 5.68 **2.864.11** 5.55) => (1.29 5.68 **2.734.22** 5.55)

5. Test System

5.1. 34 Bus Test System

The test system consists of 34 Bus, 33 Lines as shown in Fig 1. The first bus is considered as the substation bus. Loads are connected to all buses except the first bus which is the substation bus. The total real power load and reactive power load of this test system are 5051.5 kW and 3055kVAr respectively. The substation voltage is 12.66 kV.

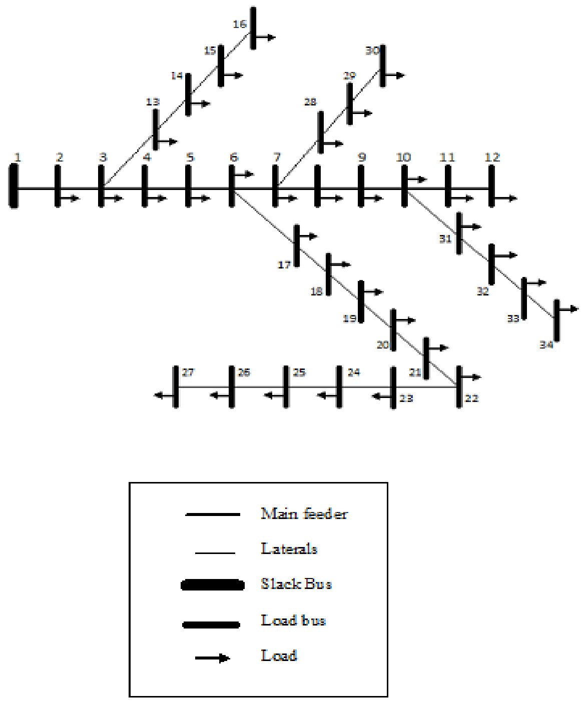

Figure 1: Line diagram of 34 bus RDS

6. Result Analysis

Before Capacitor Placement

The base case load flow was implemented on a 34 bus radial distribution system. The bus system has a substation which acts as the slack bus and 33 load buses. The main feeder consists of 12 buses starting from bus 1 till bus 12. The total connected real power load is 5051.5 kW and the total connected reactive power load is 3055 kVAr. The total connected real power load to the main feeder is 1871.5 kW and the total connected reactive power load to the main feeder is 1120.5 kVAr. The total connected real power load to the laterals is 3180 kW and that of the reactive power load is

1934.5 kVAr. The voltage constraints are assumed to be 0.95 p.u and 1.00 p.u.

The results from the base case load flow are as follows:

The maximum voltage was obtained at the 1st bus which is also the slack bus. The voltage magnitude at the slack bus was found to be 1.000 p.u. The minimum voltage was obtained at the 27th bus. The voltage magnitude at this bus was found to be 0.8894 p.u. The total real power injected at the slack bus is 4821.61 kW and the total reactive power injected at the slack bus is 2927.26 kVAr. The total real power loss was found to be 221 kW. The annual cost for real power loss per kW is $ 168. So the annual cost for a real power loss of 221 kW was found to be $ 37128.

Fig 2 shows the plot between bus numbers in x-axis and their corresponding voltage magnitudes in the y-axis. The voltage at the slack bus is 1.000 p.u. The voltage magnitudes show a steady decrease from the first bus until the 12th bus. The decrease in the voltage at the buses and the power losses are due to the deficient amount of reactive power. However there is a steep rise in the plot between bus 12 and bus 13. This is due to the fact that bus 13 is connected directly to bus 3 rather than bus 12. Same way there is a rise in the plot between bus 27 and bus 28. This is due to the fact that bus 28 is connected directly to bus 7 rather than bus 27.

The total real power load connected at bus 34 is 57 kW. The total real power load connected at bus 33 is 114 kW. The total real power injected at bus 34 is 57 kW. The total real power injected at bus 33 is 114.003 kW. The difference between total real power load and the total real power injected at bus 33 is 0.003 kW. This is the transmission loss which is occurring between bus 33 and bus 34.

After Capacitor Placement

The load flow results after capacitor placement is discussed below:

The maximum voltage was obtained at the 1st bus which is also the slack bus. The voltage magnitude at the slack bus was found to be 1.000 p.u. The minimum voltage was obtained at the 32nd bus. The voltage magnitude at this bus was found to be 0.9555 p.u. Thus by capacitor placement the voltage profile at buses has significantly improved. The total real power injected at the slack bus is 3856.631 kW and the total reactive power injected at the slack bus is 2406.144 kVAr. The total real power loss after capacitor placement was found to be 162.4 kW. The annual cost for real power loss per kW is $ 168. So the annual cost for a real power loss of 162 kW was found to be $ 27216. The decrease in the real power loss after capacitor placement is 59 kW. The decrease in the cost of the real power loss occurred is $ 9912. Thus by capacitor placement the real power losses was reduced considerably.

Table 1 shows the different locations at which capacitor banks have been placed. The candidate locations chosen for capacitor placement after sensitivity analysis are buses 4, 5, 6, 28 and 29. The cost of capacitor banks at these locations are $ 350, $ 800, $ 600, $ 900 and $ 1050 respectively.

ORDER	BUS NO.	SIZING
1	4	350
2	5	800
3	6	600
4	28	900
5	29	1050

Table 1: Capacitor Locations and Sizing

Fig 2 shows the comparison between voltage magnitudes before and after capacitor placement. Though the maximum voltage magnitude remains at 1.000 p.u, there was a significant improvement in the voltage magnitudes at every other bus. Fig 3 shows the comparison between real power loss before and after capacitor placement. There is a significant loss reduction after placement of capacitors.

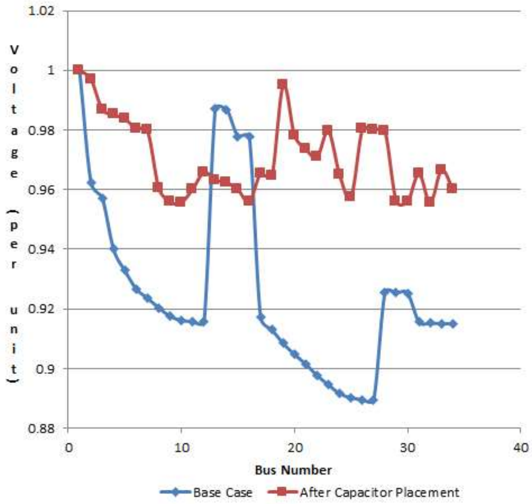

Figure 2: Comparison of voltage before and after Capacitor Placement

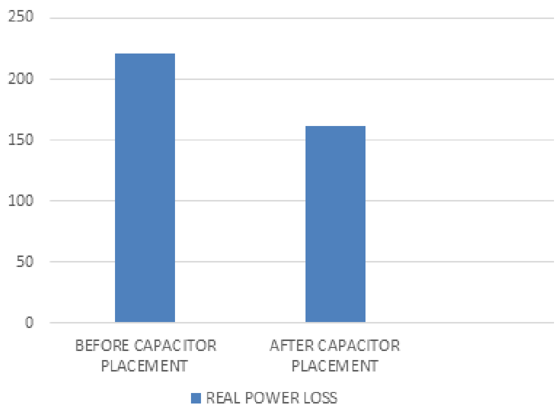

Figure 3: Comparison of Real Power Loss before and after Capacitor Placement

Table 2: Comparison with other methods

Items	*Un-Compensated*	*Compensated*			
		Su CT, Tsal CCA "fuzzy reasoning approach" IEE Proceedings 1996	Prakash, Sydulum, "PSO Approach" IEEE Proceedings 2007	R.Srinivasa Rao "PSGA method" ELSEIVER 2011	Proposed
Total Losses(kW)	221	168.47	168.8	161.7	162
Loss Reduction	-	23.999	24.85	27, 377	26.696
Total kVAr = ∑A		2700	2063	2039	3700
Total Annual Cost($)	37128	33182	29936	28484	28095
Net Savings($/year) = Annual Cost	-	4089	7306	8756	9912
% Savings	-	10.89	19.61	23.51	26.61

7. Conclusion

Overall kVA demand was reduced at each bus due to capacitor placement. The overall real power loss was reduced by optimal placement of capacitor and sizing in the 34 bus radial distribution network using Genetic Algorithm with Binary and Real Encoding. The effectiveness and superiority of our method was compared with methods used by other authors. Compared to the Fuzzy GA method [26] or PSO method [16] the losses occurred in our method is very less and almost the same as that to PGSA method [11]. The annual cost per year is the least compared to the other methods and the net savings is the highest compared to other methods. The comparison results confirmed the effectiveness and the superiority of our proposed method over other techniques. Thus our objective was achieved in this project.

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