Optimal Capacitor Placement on Interconnected Distribution Systems in Presence of Nonlinear Loads Using Genetic Algorithms

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Abstract- **Due to simplicity of analysis of radial distribution systems, all previous work studied the effect of nonlinear loads on the optimal solution of the Capacitor Placement Problem (CPP) on only radial distribution systems. The study of the optimal capacitor placement on interconnected distribution systems in presence of nonlinear loads using Genetic Algorithms (GA) is presented in this paper. Results (power losses, operating conditions and annual benefits) are compared with that obtained from radial and loop distribution systems. Computational results obtained showed that the harmonic component affects the optimal capacitor placement in all system configurations. When all loads were assumed to be linear, interconnected and Loop system configurations offer lowest power losses and best operating conditions rather than the radial system configuration while radial system configuration offer best annual benefits due to capacitor placement. In distorted networks, interconnected systems configuration offer lower power losses, best operating conditions and best annual benefits due to capacitor placement.**

I. INTRODUCTION

Electric power is supplied to final users by means of Medium Voltage (MV) or Low Voltage (LV) distribution systems, their structures and schemes can differ significantly according to loads location. Overhead lines with short interconnection capabilities are mostly employed in rural areas, whilst cables with a great number of lateral connections for alternative supplies are widespread used in urban areas.

Most power distribution systems are designed to be radial, to have only one path between each customer and the substation. The power flows exclusively away from the substation and out to the customer along a single path, which, if interrupted, results in complete loss of power to the customer. Its predominance is due to two overwhelming advantages: it is much less costly than the other two alternatives (loop and interconnected systems) and it is much simpler in planning, design, and operation.

An alternative to purely radial feeder design is a loop system, which has two paths between the power sources (substations, service transformers) and each customer. Equipment is sized and each loop is designed so that service can be maintained regardless of where an open point might be on the loop. Because of this requirement, whether operated

radially (with one open point in each loop) or with closed loops, the basic equipment capacity requirements of the loop feeder design do not change. In terms of complexity, a loop feeder system is only slightly more complicated than a radial system. Power usually flows out from both sides toward the middle, and in all cases can take only one of two routes. Voltage drop, sizing, and protection engineering are only slightly more complicated than for radial systems.

Interconnected distribution systems are the most complicated and costly but most reliable method of distributing electric power. An interconnected distribution system involves multiple paths between all points in the network. Interconnected systems provide continuity of service (reliability) far beyond that of radial and loop designs: if a failure occurs in one line, power instantly and automatically re-routes itself through other pathways.

Interconnected distribution systems are more expensive than radial distribution systems, but not greatly so in dense urban applications, where the load density is very high, where the distribution must be placed underground, and where repairs and maintenance are difficult because of traffic and congestion, interconnected systems may cost little more than loop systems. Interconnected systems require little more conductor capacity than a loop system. The loop configuration required "double capacity" everywhere to provide increased reliability. Interconnected systems is generally no worse and often needs considerably less capacity and cost, if it is built to a clever design and its required capacity margins are minimized.

The solution procedures of the Capacitor Placement Problem (CPP) start with performing a load flow analysis to analyze the steady-state performance of the power system prior to capacitor placement and after capacitor placement and to study the effects of changes in capacitor sizes and locations.

The biggest advantages of the radial system configuration, in addition to its lower cost, are the simplicity of analysis and predictability of performance. Because there is only one path between each customer and the substation, the direction of power flow is absolutely certain. Equally important, the load on any element of the system can be determined in the most straightforward manner by simply adding up all the customer loads "downstream" from that piece of equipment. Because

load and power flow direction are easy to establish in radial distribution system, voltage profiles can be determined with a good degree of accuracy without resorting to exotic calculation methods; equipment capacity requirements can be ascertained exactly; capacitors can be sized, located, and set using relatively simple procedures (simple compared to those required for similar applications to non-radial (loop and interconnected) system designs, in which the power flow direction is not a given).

The interconnected distribution systems are much more complicated than other forms of distribution, and thus much more difficult to analyze and operate. There is no "downstream" side to each unit of equipment. This complicates load estimation, power flow analysis, and protection planning.

Due to simplicity of analysis of radial distribution systems, all previous work studied the effect of nonlinear loads on optimal solution of CPP on only radial distribution systems. The study of the optimal placement and sizing of fixed capacitor banks placed on distorted interconnected distribution systems using Genetic Algorithms (GA) is presented in this paper. Results (power losses, operating conditions and annual benefits) are compared with that obtained from radial and loop distribution systems. The radial, loop and interconnected distribution systems models are obtained by suitably simplification of a typical Italian grid. Commercial package ETAP PowerStation 4.0 program is used for harmonic load flow analysis, the proposed solution methodology is implemented in Microsoft Visual Basic 6 programming language.

II. PROBLEM FORMULATION

A. Assumptions

The optimal capacitor placement problem has many variables including the capacitor size, location, capacitor cost, voltage and harmonic constraints on the system. There are switchable capacitors and fixed type capacitors in practice. However, considering all variables in a nonlinear fashion will make the placement problem very complicated. In order to simplify the analysis, only fixed type capacitors are considered with the following assumptions:
1) The system is balanced.
2) All the loads are constant

B. Capacitor size and cost

Only the smallest standard size of capacitors and multiples of this standard size are allowed to be placed at the buses to have more realistic optimal solution. The capacitor sizes are treated as discrete variable and the cost of the capacitor is not linearity proportional to the capacitor size, this makes the formulated problem a combinatorial one.

C. Objective Function

The objective of the capacitor placement problem is to reduce the total energy losses of the system while striving to minimize the cost of capacitors installed in the system. The objective function consists of two terms. The first is the cost of

the capacitor placement and the second is the cost of the total energy losses.

The cost associated with capacitor placement is composed of a fixed installation cost, a purchase cost and operational cost (maintenance and depreciation). The cost function described in this way is a step-like function rather than a continuously differentiable function since capacitors in practice are grouped in banks of standard discrete capacities with cost not linear proportional to the capacitor bank size.

It should be pointed that since the objective function is non-differentiable, all nonlinear optimization techniques become awkward to apply.

The second term in the objective function represents the total cost of energy losses. This term is obtained by summing up the annual real power losses for the system.

D. Operational Constraints

Voltages along the feeder are required to remain within upper and lower limits after the addition of capacitors on the feeder. Voltage constraints can be taken into account by specifying the upper and lower bounds of the magnitude of the voltages. The distortion of voltage is considering by specifying for maximum total harmonic distortion (THD) of voltages and the maximum number of banks to be installed in one location is taken into account.

E. Mathematical Representation

The capacitor placement problem is expressed mathematically as shown below:

$$\text{Min} \quad F = K_p \, P_{loss} + \sum_{j=1}^{J} K_j^c \, Q_j^c \tag{1}$$

Subject to:

$$V_{\min} \leq \left| V_j \right| \leq V_{\max} \tag{2}$$

$$THD_j \leq THD_{\max} \tag{3}$$

$$Q_j^c \leq Q_{\max}^c \tag{4}$$

Where

$$Q_{\max}^c = L Q_0^c \tag{5}$$

F The total annual cost function.

K_p Annual cost per unit of power losses.

P_{loss} The total power losses.
     (Result from ETAP PowerStation Harmonic Load Flow Program).

J Number of buses.

K_j^c The capacitor annual cost/kvar.

Q_j^c The shunt capacitor size placed at bus j.

V_j The rms voltage at bus j.
     (Result from ETAP PowerStation Harmonic Load

Flow Program).

V_{min} Minimum permissible rms voltage.

V_{max} Maximum permissible rms voltage.

THD_j The total harmonic distortion at bus j.
(Result from ETAP PowerStation Harmonic Load Flow Program).

THD_{max} Maximum permissible total harmonic distortion.

Q^c_{max} Maximum permissible capacitor size.

L An integer.

Q^c_0 Smallest capacitor size.

Bounds for (2), (3) are specified by the IEEE-519 standard [1].

III. GENETIC ALGORITHM

A. Solution Algorithm

Combinatorial optimization problems can be solved either by exact or by approximate methods. In exact methods, all the feasible solutions are evaluated and the best one is selected as the optimal solution. However, exact methods are impractical when a real-life problem is to be evaluated. In this paper, GA will be used for the solution of CPP.

B. Genetic Algorithm Framework

There are four components in the design of a GA-based solution methodology. These include the initialization of the algorithm, fitness evaluation, selection and genetic operators.

Algorithm initialization is the process of randomly generating a set of initial feasible solutions forming the so-called "initial population". The number of these solutions is referred to as the "population size". Each iteration in a genetic algorithm, known as a "generation", results in a new set of feasible solutions.

Genetic algorithm needs some fitness measure to determine the relative 'goodness' of a particular solution. This can be obtained either by direct evaluation of the objective function or by some other indirect means. Fitness evaluation is the criterion guiding the search process of a genetic algorithm.

In genetic algorithms, parents are selected to produce offspring. Selection process can be carried out in different ways as discussed before in chapter three.

Genetic operators are the probabilistic transition rules employed by a genetic algorithm. A new and improved population is generated from an old one by applying genetic operators. Operators used by genetic algorithms include crossover and mutation.

Crossover is the process of choosing a random position in the solution and swapping the characters around this position with another similarly partitioned solution. The random position is referred to as "the crossover point". In other words, crossover defines the outcome as gene exchange. Crossover operator proved very powerful in genetic algorithms. Mutation is the process of random modification of a particular value of a solution with a small probability. Mutation is applied to alter some genes in the solutions. When a gene exchange resulting from application of a crossover operator is not meeting appropriate restriction, mutation might be very helpful in providing a proper gene exchange amendment. Mutation is generally seen as a background operator that provides a small amount of random search. It increases the population diversity. It also helps expand the search space by reintroducing information lost due to premature convergence. Therefore, it drives the search into unexplored regions.

In addition to the above components, the stopping criterion of the algorithm is of great significance. It determines when the algorithm shall be stopped or terminated and thus, considering the best solution obtained so far as the optimal solution.

C. Design of a successful GA-based solution methodology

In designing a GA-based solution methodology, several decisions concerning the algorithm parameters shall be properly made in order to obtain high-quality solutions. Premature convergence to local optimum may result if the algorithm parameters are not selected in an appropriate manner.

Population size and the way the initial population is selected will have a significant impact on the results. Initial population could be seeded with heuristically chosen solutions or at random. In either case, the initial population should contain a wide variety of structures. The population size and the initial population are selected such that the solution domain associated with the population is sufficiently covered. The population size depends on the criteria for selecting the initial solutions. A constant size population of solutions shall be judged by the algorithm designer. If the population size is too small, the solution domain will not be adequately searched and, thus, resulting in poor performance. Premature convergence to local solutions can be prevented by using a large population size. However, this may slow down the convergence rate.

The performance of a genetic algorithm is highly sensitive to the fitness values. The fitness value may be selected as the objective function to be optimized. Some researchers, however, believe that the objective function value is a naive fitness measure. Therefore, using the objective function value associated with each solution as a fitness measure is rarely a good idea to some researchers. When applying a crossover operator, the resulting offspring can be either feasible of infeasible. There are two ways to deal with infeasible solutions. One way is to design heuristic operators transforming infeasible solutions to feasible ones. The second is by penalizing this infeasibility in the objective function. In the latter case, selection of proper penalty factors is another decision to be made by the algorithm designer.

Crossover rate and mutation rate play a very important role in the performance of genetic algorithm. A higher crossover rate introduces new solutions more quickly into the population. If the crossover rate is too high, high-performance solutions are eliminated faster than selection can produce improvements. A low crossover rate may cause stagnation due to the lower exploration rate. Mutation rate shall not be too high in order not to prevent crossover from doing its work properly. Some researchers reported that a variable mutation rate rather than a fixed one is more beneficial to be utilized. In the initial stage of the GA, it is recommended to start with a high crossover rate and a low mutation rate since the crossover is mainly responsible for the search at this stage. As the algorithm progresses, the crossover operator becomes less productive and therefore, the mutation rate shall be increased.

Simple GA involving just mutation and crossover has proved to be quite powerful enough. Some designers proposed to add an inversion operator where a section of a solution is 'cut out' and then re-inserted reversely. However, it has not been found significantly useful. It may be used instead of mutation operator to explore new regions of the searching domain.

As pointed out earlier, newly generated solutions replace existing solutions in subsequent generations of GA. Two replacement approaches are available to the algorithm designer to select among which. These are the incremental or 'steady-state' approach and the generational approach. In incremental or steady state replacement, once a new feasible solution has been generated, it will replace an above-average fitness value member chosen randomly. Members that fitness values are better than the calculated average are transferred to the next generation with no change. In generational replacement a new population of children is generated to replace the whole parent population. The steady-state replacement approach has the following advantages.

1. If steady-state replacement approach is not employed, there will be no guarantee that the best solution in the current population will survive into the next generation. With this approach, best solutions are always kept in the population and the newly generated solution is immediately available for selection and reproduction.
2. It is more efficient when compared to the generational approach. Faster convergence is usually expected with this approach.
3. It prevents the occurrence of duplicates. Duplication is unhelpful since it wastes resources on evaluating, the same fitness function and it distorts the selection process by giving extra chances to the duplicate solutions to reproduce.

Researchers, however, reported some success with the generational replacement approach. The genetic algorithm can be designed to stop if a pre-specified number of iterations are completed or if no improvement is encountered in the optimal solution during a given number of consecutive iterations. The stopping criterion shall be properly tuned with the other parameters like the population size, crossover rate and mutation rate in order to obtain a high quality solution.

D. Application of GA to the CPP in distorted distribution systems

Because of its simplicity, generality and ability to cope with practical constraints, a genetic algorithm has been designed to solve the general CPP in a distribution system. The following remarks shed some light on the design aspects of the algorithm as applied to the CPP:

- The population size is a fixed value and the same is determined empirically by trial and error process.
- The objective function itself is used to provide fitness values of the newly generated solutions. Once a new solution is generated, its associated feasibility is checked. If the solution is infeasible, the penalty factor is applied.
- Selection, crossover and mutation are applied as genetic operators in the algorithm design. No additional operators such as the inversion operator are considered in the design process.
- The algorithm is designed based on a fixed, rather than a variable, mutation rate throughout the search.
- Steady-state replacement approach is selected in the design of the algorithm.
- The algorithm is designed to stop after predetermined number of generation.

Based on the above remarks, a GA-based solution methodology applied to the CPP has been implemented. The algorithm implementation can be summarized as follows:

In this paper the representation by means of strings of integers was chosen. Each gene(i) (represent buses) of the chromosome (its length is equal to the total number of the system buses (m)) can store a 0, which indicates absence of capacitors on the corresponding bus or an integer different from 0 that indicates the number of added capacitor sizes that is added in the bus(i). Therefore a chromosome can be represented as Figure (1)

Bus number	1	2	3	...	...	m-2	m-1	m
gene	0	3	4	...	...	2	1	3

Figure 1: A genetic algorithm chromosome of the capacitor placement problem

The algorithm procedure can be summarized as follow:
1. Input GA parameters, i.e. population size, crossover rate, mutation rate, selection type, crossover type, mutation type and termination mode.
2. Generate a set of initial solutions, forming the initial population, randomly.
3. Run ETAP Power Station 4.0 program to calculate system power losses, bus voltages and total harmonic distortion at each bus.
4. Calculate the associated fitness value (objective function) of each solution.
5. Check the constraints and applying the penalty factor (by adding 1E10 to the fitness value) if the constraints is not satisfied.
6. Create a new population by performing selection,

crossover and mutation on the individuals.

7. Discard the old population and iterate using the new population if the stopping criterion is not satisfied.

IV. NUMERICAL RESULTS

A. Test System data

The distribution network models are obtained by suitably simplification of a typical Italian grid [2]. Single line diagram of the network is shown in Fig. (2) and the system data as follows:

Two 132 kV HV networks with the same short circuit power MVAsc of 6000 MVA;

Two HV/MV substations, comprising each a 132 kV HV busbar, a 132/20 kV 40 MVA transformer and a 20 kV MV busbar;

A feeder, subdivided in three line sections (L01, L12 and L23) of 3 km each with % positive sequence impedance (100 MVA base) R=5.17, X=4.23, Z=6.68

A series of further passive overhead feeders;

Link lines between various feeder (Lm1 and Lm2);

Configuration switches (S1, S2, S3, S4, S5 and S6).

Table (1) show the system load data

The proposed GA was applied to the test system-2 for three different network configurations:

1. Radial configuration (S1 open, S2 open, S3 open, S4 open, S5 open and S6 open);
2. Loop configuration (S1 open, S2 open, S3 close, S4 close, S5 close and S6 close);
3. Interconnected configuration (S1 close, S2 close, S3 open, S4 open, S5 open and S6 open).

Table (1): Test system load data

Bus No.	Load (80% motor, 20% static)	
	MW	MVAR
1	5.25	5.356
2	5.25	5.356
3	5.25	5.356
4	4.5	2.18
5	4.5	2.18
6	4.5	2.18
7	4.5	2.18
8	4.5	2.18
9	4.5	2.18
10	4.5	2.18
11	4.5	2.18
12	4.5	2.18

Commercially-available capacitor sizes with real costs/kvar were used in the analysis. It was decided that the largest capacitor size Qcmax should not exceed the total reactive load, i.e., 35688 kvar. The yearly costs of capacitor sizes as described in [3]

Optimum shunt capacitor sizes have been evaluated for the following cases:

- Case (1): All loads are assumed to be linear
- Case (2): Each 40 MVA transformer has harmonic current

source –typical IEEE- XFMR Magnet.

Kp was selected to be 168 \$/kW, and the voltage limits on the rms voltages were selected as Vmin= 0.95 pu, and Vmax=1.05 for case (1) and Vmin= 0.93 pu, and Vmax=1.05 for case (2). The maximum THD was selected as THDmax = 5

B. Test System results

Table (2) Comparison of results between radial, loop and interconnected distribution systems for case (1)

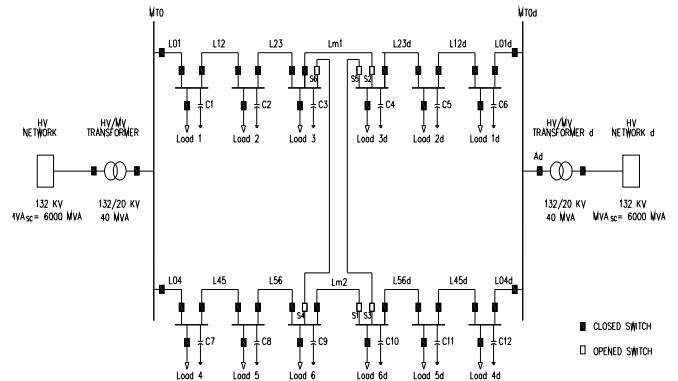| Variable	Before OCP			Case (1)		
	Radial	Loop	Interconnected	Radial	Loop	Interconnected
Q_{C1} (kvar)	---	---	---	4050	3600	3900
Q_{C2} (kvar)	---	---	---	3900	4050	4050
Q_{C3} (kvar)	---	---	---	4050	3900	3600
Q_{C4} (kvar)	---	---	---	1500	1800	3600
Q_{C5} (kvar)	---	---	---	3300	2400	3300
Q_{C6} (kvar)	---	---	---	1650	2700	2100
Q_{C7} (kvar)	---	---	---	3450	3300	3450
Q_{C8} (kvar)	---	---	---	750	3300	2400
Q_{C9} (kvar)	---	---	---	3450	3450	2400
Q_{C10} (kvar)	---	---	---	1800	2400	1200
Q_{C11} (kvar)	---	---	---	2250	2550	2100
Q_{C12} (kvar)	---	---	---	2700	1650	2250
Total capacitor (kvar)	---	---	---	32850	35100	34350
Min. voltage(pu)	0.91	0.91484	0.92671	0.96535	0.97364	0.97521
Max. voltage(pu)	0.95516	0.95516	0.94462	0.98778	0.98860	0.98554
Power losses (kW)	1244.1	1211.1	1206.5	812.8	795.7	796.8
Cap. cost (\$/year)	---	---	---	6142.8	6301.65	6156.9
Total cost (\$/year)	209008	203464	202692	142685	139904	139952
Benefits (\$/year)	---	---	---	66323	63560	62739

Figure 2: Test system - Simplified Typical Italian Grid

Table (3) Comparison of results between radial, loop and interconnected distribution systems for case (2)

| Variable	Before OCP			Case (2)		
	Radial	Loop	Interconnected	Radial	Loop	Interconnected
QC1 (kvar)	---	---	---	2700	900	3600
QC2 (kvar)	---	---	---	3000	3150	3450
QC3 (kvar)	---	---	---	2550	3450	3150
QC4 (kvar)	---	---	---	1350	2100	2700
QC5 (kvar)	---	---	---	2100	1650	1800
QC6 (kvar)	---	---	---	2100	2850	750
QC7 (kvar)	---	---	---	300	2400	1650
QC8 (kvar)	---	---	---	2850	2100	1800
QC9 (kvar)	---	---	---	2550	2550	1650
QC10 (kvar)	---	---	---	3450	2400	3000
QC11 (kvar)	---	---	---	900	1350	3600
QC12 (kvar)	---	---	---	3000	2400	300
Total capacitor (kvar)	---	---	---	26850	27300	27450
Min. voltage(pu)	0.9099	0.9148	0.92669	0.948	0.9544	0.9649
Max. voltage(pu)	0.9551	0.9551	0.94461	0.98657	0.9866	0.9772
Max. THD (%)	2.68	2.68	2.65	4.95	4.99	4.96
Power losses (kW)	1244.2	1211.1	1206.5	873.7	844.928	828.92
Cap. cost ($/year)	---	---	---	5007	4992	5135
Total cost ($/year)	209031	203474	202707	151788	146940	144413
Benefits ($/year)	---	---	---	57242.9	56534	58293
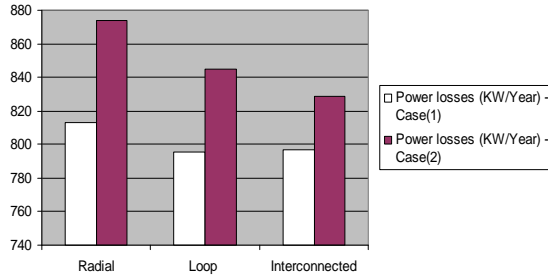
Figure 3: Power losses (Kw/year) for case (1) & (2)

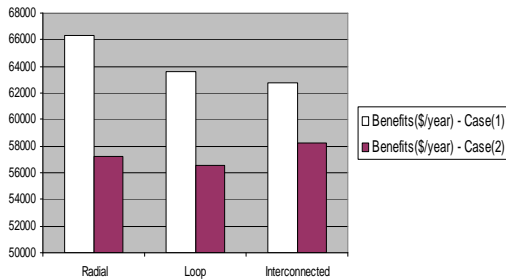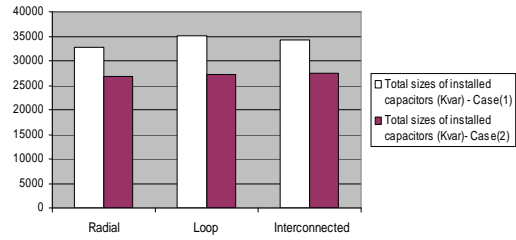Figure 4: Benefits ($/year) for case (1) & (2)

Figure 5: Total sizes of installed capacitors (Kvar) for case (1) & (2)

V. CONCLUSION

The study of the optimal capacitor placement on interconnected distribution systems in the presence of nonlinear loads using Genetic Algorithms (GA) is presented in this paper. Results (power losses, operating conditions and annual benefits) are compared with that obtained from radial and loop networks. The radial, loop and interconnected distribution systems models are obtained by suitably simplification of a typical Italian grid. Computational results obtained showed that the harmonic component affects the optimal capacitor placement in all system configurations. When all loads were assumed to be linear, interconnected and Loop system configurations offer lowest power losses and best operating conditions rather than the radial system configuration while radial system configuration offer best annual benefits due to capacitor placement. In distorted networks, interconnected systems configuration offer lower power losses, best operating conditions and best annual benefits due to capacitor placement.

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