Optimal Sizing of Fixed Capacitor Banks Placed on a Distorted Interconnected Distribution Networks by Genetic Algorithms

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Abstract- **In this paper, the optimal sizing of fixed capacitor banks problem in a distorted interconnected distribution system is formulated and solved by a Genetic Algorithm (GA) solution technique to minimize the cost of power production and capacitor banks under the constraints include voltage limits , sizes of installed capacitors and Total Harmonic Distortion (THD), the algorithm is applied on IEEE 30-bus test system and the results are given for different cases: Light and heavy harmonic cases. Computer simulation shows that the harmonic components affect the optimal capacitor sizing.**

I. INTRODUCTION

Capacitors have been commonly used to provide reactive power compensation in distribution systems in order to reduce power losses, regulate bus voltage and improve power factor. The capacitor placement problem is a well-researched topic. Earlier approaches differ in problem formulation and the solution methods. In some approaches, the objective function is considered as an unconstrained problem [1]. Some have formulated the problem as constrained optimization and included voltage constraints into consideration [2].

Capacitor values are often assumed as continuous variables whose costs are considered as proportional to capacitor size in past researches [3], [4]. However, commercially available capacitors are discrete capacities and tuned in discrete steps. Moreover, the cost of capacitor is not linearly proportional to the size (kVar). Hence, if the continuous variable approach is used to choose integral capacitor size, the method may not result in an optimum solution and may even lead to undesirable harmonic resonance conditions.

While most works have been studied by many researchers on capacitor placement in balanced distribution system , very few research is related to capacitor placement in unbalanced distribution systems [5]-[7].

In today's power system, there is a general trend to use more nonlinear loads such as energy-efficient fluorescent lamps and solid-state devices. The capacitors' sizing and allocation should be properly considered, if else they can amplify harmonic currents and voltages due to possible resonance at one or several harmonic frequencies. This condition could lead to potentially dangerous magnitudes of harmonic signals, additional stress on equipment insulation, increased capacitor failure and interference with communication system [8].

Most of the reported techniques for capacitor placement assume sinusoidal operating conditions. These methods include: nonlinear programming [9], near global methods (genetic algorithms [10]-[16], simulated annealing [17]-[20], tabu search [21] - [24], artificial neural networks [25] and fuzzy set theory [26], [27]). All these approaches ignore the presence of voltage and current harmonics.

Some of the recent publications have taken into account the presence of distorted voltages for solving the capacitor sizing problem. These investigations include: exhaustive search [28], local variations [29], mixed integer-nonlinear programming [30], heuristic methods for simultaneous capacitor and filter placement [31], maximum sensitivities selection and fuzzy set theory [32], genetic Algorithm [33], partial swarm optimization [34].

All above publications have discussed on radial networks, the present paper GA employed to determine the optimal sizing of fixed capacitor banks in an interconnected distribution network with non sinusoidal substation voltages, Commercial package ETAP PowerStation program [35] is used for harmonic load flow analysis.

Many programming languages were used to implement the solution algorithm such as Turbo Pascal [10], C++ [11], FORTRAN [17], Turbo C [22], Borland C [23], and MATLAB [33]. In this paper the solution algorithm was implemented using Microsoft Visual Basic 6 programming language, shown in Figure 1, which is not just a language to program in but a whole graphical development environment.

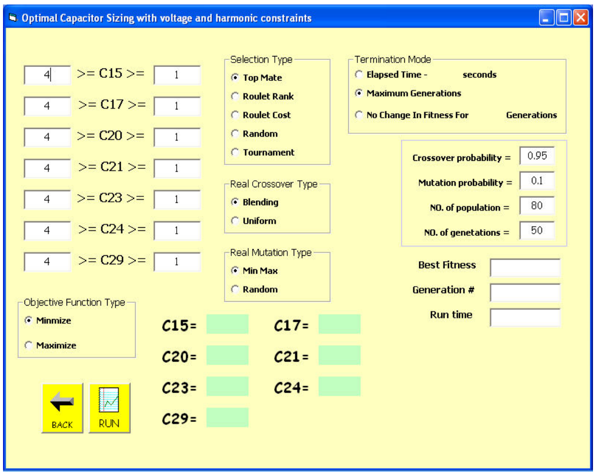
II. HARMONIC LOAD FLOW STUDY

Using computer simulation, the phenomena of power system harmonics can be modeled and analyzed. The ETAP PowerStation Harmonic Analysis program shown in Figure 2 provides a tool to accurately model various power system components and devices to include their frequency dependency, non-linearity, and other characteristics under the presence of harmonic sources.

Total Harmonic Distortion (THD), is the most popular index to measure the level of harmonic distortion to voltage and current. It is a measure that shows the ratio of the mean-square-root of all harmonics to the fundamental component. For an ideal system, THD is equal to zero. THD is determined by:

$$THD = \frac{\sqrt{\sum_{2}^{\infty} F_i^2}}{F_1}$$

Where F_i is the amplitude of the ith harmonic, and F_1 is that for the fundamental component.



Optimal Capacitor Sizing with voltage and harmonic constraints

4 >= C15 >= 1
4 >= C17 >= 1
4 >= C20 >= 1
4 >= C21 >= 1
4 >= C23 >= 1
4 >= C24 >= 1
4 >= C29 >= 1

Selection Type
● Top Mate
○ Roulet Rank
○ Roulet Cost
○ Random
○ Tournament

Termination Mode
○ Elapsed Time - seconds
● Maximum Generations
○ No Change In Fitness For Generations

Crossover probability = 0.95
Mutation probability = 0.1
NO. of population = 80
NO. of genetations = 50

Real Crossover Type
● Blending
○ Uniform

Real Mutation Type
● Min Max
○ Random

Best Fitness
Generation #
Run time

Objective Function Type
● Minmize
○ Maximize

C15=
C17=
C20=
C21=
C23=
C24=
C29=

Figure 1. Optimal Capacitor Sizing Program Using VB6

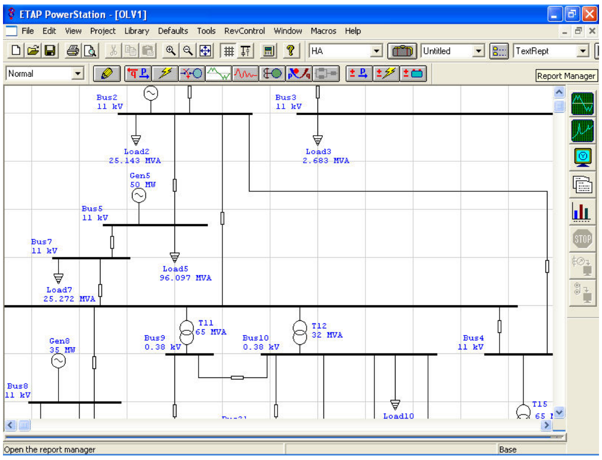


Figure 2. ETAP PowerStation Harmonic Analysis program

The Harmonic Load Flow Study first carries out a load flow calculation at the fundamental frequency. The results of the fundamental load flow sets the base for the fundamental bus voltage and branch currents which are used later to calculate different harmonic indices. Then, for each harmonic frequency at which any harmonic source exists in the system, a direct load flow solution is found by using the current injection method. The harmonic frequencies considered are all the low order frequencies from the 2nd to the 15th, plus the characteristic harmonics from the 17th up to the 73rd. Impedance of components is adjusted based on the harmonic frequencies and the types of components. For a triple harmonic frequency, zero sequence impedance is adjusted to the actual frequency and the zero sequence network is used.

From the harmonic load flow calculation, the harmonic components for bus voltages and branch currents are found, and then all harmonic indices are computed accordingly. The computed bus THD are compared with their limits as specified the IEEE-519 standard [8].

Non-linear loads in power systems are essentially either injecting harmonic currents into the system or applying harmonic voltages at the given points. Therefore, they are conventionally modeled as current sources and voltage sources with harmonic frequencies. Normal power sources such as power grids or generators, if they contain harmonic components in their fixed voltages, are modeled as voltage sources with harmonic frequencies.

A. Harmonic Current Source

Non-linear loads that can be modeled as a harmonic current source in PowerStation are:

1) Static Load
2) UPS (Uninterruptible Power Supply)
3) Charger/Converter
4) VFD (Variable Frequency Drive)
5) Transformer

Static loads, chargers/converters and VFDs, if they are modeled as a harmonic current source, will inject harmonic current into the connected buses.

When a saturated transformer contributes significant harmonic current into the system (most likely when the transformer is lightly loaded), it can also be modeled as a harmonic current source. Harmonic current source generated by a transformer is normally placed at the primary side; however, if there is a triple nth harmonic current specified for a transformer and the transformer winding and ground connections do not allow the triple nth harmonic current to flow in the primary winding, the secondary side and then the tertiary side will be considered as the location for the harmonic current source.

When a UPS is modeled as a load, it injects harmonic current into the connected bus. On the other hand, if a UPS is modeled as a branch, then it will inject harmonic current into both the AC input bus and the AC output bus. As a result, the path from the AC input bus to the AC output bus inside the UPS will be opened in harmonic load flow calculations.

B. Harmonic Voltage Source

The following components can be modeled as a harmonic voltage source in PowerStation:

1) Power Grid
2) Synchronous Generator
3) Inverter
4) Charger/Converter
5) Static Load

“Polluted” power grids (utilities) or saturated synchronous generators can be modeled as harmonic voltage sources if they contain significant voltage distortion.

Inverters, chargers/converters, and static loads can also be modeled as harmonic voltage sources if they primarily cause voltage distortion instead of current distortion.

III. PROBLEM FORMULATION

A. Assumptions

The optimal capacitor sizing problem has many variables including the capacitor size, capacitor cost, and voltage & 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 sizing problem very complicated. In order to simplify the analysis, only fixed-type capacitors are considered with the following assumptions:

1) *Balanced conditions.*
2) *Time-invariant loads.*

B. Objective Function

Most papers consider the transmission loss in the objective function. However, the minimization of loss does not guarantee the minimization of the operation cost unless all units have the same efficiency. Therefore the fuel cost has been used [37].

The objective function used for capacitor sizing is:

Min. $C = C_F + C_C$ (1)

$$C_F = \sum_{i \in N_g} C_i(P_i) \quad (2)$$

$$C_i = \begin{cases} a_{i1} + b_{i1}P_i + c_{i1}P_i^2 & if\ \underline{P_i} \le P_i < P_{i1} \\ a_{i2} + b_{i2}P_i + c_{i2}P_i^2 & if\ P_{i1} \le P_i < P_{i2} \\ \cdots & \\ \cdots & \\ \cdots & \\ a_{im} + b_{im}P_i + c_{im}P_i^2 & if\ P_{im-1} \le P_i < \overline{P}_i, \end{cases} \quad (3)$$

Where

C_F: the total power production cost, or more specifically the total summation of generators fuel costs,

C_C: the cost of fixed capacitors,

N_g: the set of generators,

$C_i(P_i)$: cost of the i^th generator,

a_{ij}, b_{ij}, c_{ij}: cost coefficients of the ith generator at the jth power level,

P_i: the generated power of the ith generator [MW],

$\underline{P_i}$, $\overline{P}_i$: minimum and maximum real power generation of the ith generator.

C. Constraints

The objective function to minimize the total cost with the following constraints:

$$V_{\min} \le \left|V_j\right| \le V_{\max} \quad \text{for j=1, ……., n} \quad (4)$$

$$THD_j \le THD_{\max} \quad \text{for j=1, ……., n} \quad (5)$$

Bounds for (4), (5) are specified by the IEEE-519 standard [8].

$Q^c_{\max} = L\, Q^c_o$

Where:

$Q^c_{\max}$: maximum capacity of the installed capacitor,

L: an integer,

Q^c_o: smallest capacitor size.

IV. GENETIC ALGORITHM

Genetic Algorithm (GA) [38] was first proposed by Holland in the early 1975s [39]. It is an adaptive method simulating the evolutionary process in nature and is based on the principle of nature selection and best survival.

Genetic algorithm is different from other heuristic methods in several ways. The most important difference is that a GA works on a population of possible solutions, while other heuristic methods use a single solution in their iterations. Another difference is that GA is probabilistic (stochastic), not deterministic.

A genetic algorithm approach is developed for optimizing shunt capacitor sizes in interconnected distribution systems with the consideration of harmonic distortion limit.

The genetic algorithm was implemented using optiGA ActiveX control [40] which implements a width range of features as shown on Table I.

TABLE I
OPTIGA FEATURES

Data types	Binary, Real, Integer
Selection methods	Top mate, Roulette rank/cost, Tournament, Random
Crossover methods	One/Two points, Uniform, Blending, User defined
Mutation methods	Flip bit, Random, Min/Max, User defined
Termination methods	Maximum generation, Elapsed time, No change in fitness
Objective function	Minimum, Maximum

Broadly well known, GA is the search method which can consume much time, while finding the global solution; however, in designing and planning of distribution systems, the computation speed searching the optimal solution is not so important. This fact allows one to apply GA if needing an exact solution instead of the computation time.

The genetic algorithm consists of the following main components:

A. Chromosomal Representation

Each chromosome represents a legal solution to the problem and is composed of a string of genes. The binary alphabet {0, 1} is often used to represent these genes but sometimes, depending on the application, integers or real numbers are used. In fact, almost any representation can be used that enables a solution to be encoded as a finite length string.

B. *Initial Population*

Once a suitable representation has been decided upon for the chromosomes, it is necessary to create an initial population to serve as the starting point for the genetic algorithm. This initial population is usually created randomly. From empirical studies, over a wide range of function optimization problems, a population size of between 30 and 100 is usually recommended.

C. *Fitness Evaluation*

Fitness evaluation involves defining an objective or fitness function against which each chromosome is tested for suitability for the environment under consideration. As the algorithm proceeds we would expect the individual fitness of the "best" chromosome to increase as well as the total fitness of the population as a whole.

D. *Selection*

We need to select chromosomes from the current population for reproduction. If we have a population of size 2N, the selection procedure picks out two parent chromosomes, based on their fitness values, which are then used by the crossover and mutation operators (described below) to produce two offspring for the new population. This selection /crossover /mutation cycle is repeated until the new population contains 2N chromosomes i.e. after cycles. The higher the fitness values the higher the probability of that chromosome being selected for reproduction. Here are the selection methods implemented with optiGA:

1) *Top mate*

The first parent is selected by the fitness order. The second parent is selected randomly.

2) *Roulette rank/cost*

With this selection method, the chance of a chromosome to be selected is calculated according to their fitness (cost) or according to their rank.

3) *Tournament*

With this selection method, a small subset of chromosomes is selected and the one with the best fitness will become a parent.

4) *Random*

This is the simplest method. Parents are simply selected randomly.

E. *Crossover*

After two parents have been selected by the selection method, crossover takes place. Crossover is an operator that mates the two parents (chromosomes) to produce two offspring. The two newborn chromosomes may be better than their parents and the evolution process may continue. The crossover in carried out according to the crossover probability. Here are the crossover methods implemented by optiGA:

1) *One point*

A random crossover point is selected. The first part of the first parents is hooked up with the second part of the second parent to make the first offspring. The second offspring is build from the first part of the second parent and the second part of the first parent (the crossover point is noted by the | sign):

Parent #1: 011101|0101
Parent #2: 100111|0111
Offspring #1: 011101|0111
Offspring #2: 100111|0101

(This method is implemented for binary genes only).

2) *Two points*

The two points crossover operator differs from the one point crossover in the fact that two crossover points are selected randomly:

Parent #1: 011|101|0101
Parent #2: 100|111|0111
Offspring #1: 011|101|0111
Offspring #2: 100|111|0101

(This method is implemented for binary genes only).

3) *Uniform*

In the uniform crossover each bit/gene is selected randomly, either from the first parent or from the second one:

Parent #1: 0111010101
Parent #2: 1001110111
Offspring #1: 0111010111
Offspring #2: 1001110101

4) *Blending*

This crossover operator is a kind of linear combination of the two parents that uses the following equations for each gene:

Offspring #1 = parent1 – b * (parent1 – parent2)
Offspring #2 = parent2 + b * (parent1 – parent2)

Were b is a random value between 0 and 1. (This method is implemented for real and integer genes only).

5) *User defined*

The user defined crossover method is the most powerful one. With this method the user may code his own crossover operator, so the sky is the limit.

F. *Mutation*

Mutation is the genetic operator that randomly changes one or more of the chromosome's gene. The purpose of the mutation operator is to prevent the genetic population from converging to a local minimum and to introduce to the population new possible solutions. The mutation is carried out according to the mutation probability. Here are the mutation methods implemented by optiGA:

1) *Flip bit*

This mutation method simply changes (flips) a randomly selected bit:

Before mutation: 0111010101
After mutation: 0111000101

(This method is implemented for binary genes only).

2) *Random*

The random mutation operator exchange's a random selected gene with a random value within the range of the gene's minimum value and the gene's maximum value. (This method is implemented for real and integer genes only).

3) *Min-max*

The min-max mutation operator exchange's a random selected gene with the gene's minimum value or with the gene's maximum value, selected randomly. (This method is implemented for real and integer genes only).

4) User defined

The user defined mutation method is the most powerful one. With this method the user may code his own mutation operator, so the sky is the limit.

G. Termination

The termination method determines when the genetic process will stop evolving. Here are the termination methods implemented by optiGA:

1) Maximum generations

The genetic process will end when the specified number of generation's have evolved.

2) Elapsed time

The genetic process will end when a specified time has elapsed.

Note: if the maximum number of generation has been reached before the specified time has elapsed, the process will end.

3) No change in fitness

The genetic process will end if there is no change to the population's best fitness for a specified number of generations.

Note: if the maximum number of generation has been reached before the specified number of generation with no changes has been reached, the process will end.

V. NUMERICAL RESULTS

The solution algorithm was implemented using Microsoft Visual Basic 6 programming language and was executed on a P IV personal computer, Harmonic load flow analysis was implemented by Commercial package ETAP PowerStation program.

The test system is an IEEE 30-bus interconnected network, as the system and load data can be referred to [41].

The capacitor size are regarded as discrete variable and as multiple of a standard bank (2.5Mvar), with investment cost of 0.05 $/hr. For practical installation space consideration, maximum capacity of the installed capacitor is of four banks (10Mvar). In this paper, the candidate buses for capacitor installation are as [37]. The parameters used through the simulation are shown in table II.

Harmonic sources data for case II and case III are shown in table III.

The results are shown in table IV for three different cases; first when all the loads are assumed to be linear, second when light loads are non-linear and finally when all the loads are assumed to be non-linear.

VI. CONCLUSION

A study of the effect of the system harmonics on calculating the optimum capacitor size , as well as the total cost, for interconnected distribution networks is presented at this work. A genetic algorithm approach is used. The programming is achieved using Visual Basic 6. Commercial package ETAP PowerStation program is used for harmonic load flow analysis, optimal capacitor sizing program used in this work is most effective, simple to use, and it gives better results than that indicates at [37].

Three different cases are introduced; the first with all loads are linear, the second with light loads are non-linear and the third one is the extreme case with all the loads are nonlinear. It was found that the optimal sizes of the capacitors have increased by 12.5% in the case of light harmonics and 37.5% in the heavy harmonic case. Computer simulation shows that the harmonic components affect the optimal capacitor sizing.

TABLE II
SIMULATION PARAMETERS

Crossover probability	0.95
Mutation probability	0.1
NO. of population	80
NO. of generations	50
Data type	Integer
Selection method	Top mate
Crossover method	Blending
Mutation method	Min/Max
Termination method	Maximum generation
Objective function	Minimum

TABLE III
HARMONIC SOURCES DATA

CASE II			
Load No.	Type	Manufacturer	Model
2,7,24	Current Source	Typical IEEE	12 pulse VFD
21	Current Source	Rockwell	12 pulse VFD
CASE III			
2,3,7,15,20 , 24,29	Current Source	Typical IEEE	12 pulse VFD
17,21	Current Source	Rockwell	12 pulse VFD
26	Current Source	Rockwell	6 pulse VFD

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