ENHANCEMENT OF DISTRIBUTION SYSTEMS PERFORMANCE USING MODERN OPTIMIZATION TECHNIQUES

B. Sc. Project

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##### ABSTRACT

The major loads are connected to the network through the distribution systems. Therefore, the quality of the service is based on the continuity of power and maintaining the supply voltage within certain limits with specified frequency. Due to the rapid spread in the loads, the long distance of radial structure and the high R/X ratio of lines, the power loss reduction and voltage profile improvement are the challenge. To solve these problems, the distributed generations (DGs) and shunt capacitors are installed on the radial feeders for active and reactive power injections. Therefore, the optimal locations and sizes of DGs and capacitors in distribution systems can be formulated as a constrained optimization problem. In order to solve this problem, the optimization techniques are applied

This project presents a procedure to determine the optimal placement of DGs and capacitors with an objective of power loss minimization or total voltage deviation minimization. The Archimedes Optimization Algorithm (AOA) is introduced to find the optimal locations and sizes of DGS and Capacitors considering the minimization of total power loss or TVD as objective function, while the security and operational constraints are fully achieved. The backward/forward sweep (BFS) algorithm is introduced for the load flow calculations. The proposed procedure is applied on 34-bus standard radial distribution system and East Delta Network (EDN) distribution system as a part of the Unified Egyptian Network (UEN) in order to solve the optimal DGs and capacitors placement problem. The obtained results are compared with other methods. Simulation results show the capability of the proposed procedure to find the optimal solution for significant minimization in the objective function with more accuracy and efficiency.

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# Distributed Generation and Capacitor Technologies

## Introduction

Recently, electric grid was designed to operate as a vertical structure consisting of generation, transmission and distribution and supported with controls and devices to maintain reliability, stability and efficiency. However, system operators are now facing new challenges including the penetration of renewable energy resources (RER) in the legacy system, rapid technological change and different types of market players and end users.

Enhancement of distribution system performance requires modeling of renewable energy sources and technologies such as wind, photovoltaic (PV), solar, biomass and fuel cells, analyzing their levels of penetration and conducting impact assessments of the legacy system for the purpose of modernization. The roadmap envisions widespread deployment of distributed energy resources (DERs) in the near future. Renewable energy technologies and their integration introduce several issues including enhancement of efficiency and reliability and the development of state of the art tracking to manage variability. Architecture designs, which include optimal interconnections, optimal sizing and siting DERs for optimum reliability, security and economic benefits are also critical aspects [19].

In this chapter, the different types, benefits and applications of distributed generation (DG) are presented in the distribution networks. In addition, the fixed and switched capacitor banks are presented to improve the distribution network reliability.

## Distributed Generations (DGs)

DG is not a new concept. A number of utility consumers have been using DG for decades. Over the last 10 years, the DG market has been somewhat turbulent. In the late 1990s, new regulations/subsidies, such as net metering and renewable portfolio requirements, and the development of new DG technologies have sparked broader interests in DG [9].

### Definition of DG

DG generally applies to relatively small generating units of 30 MW or less sited at or near customer sites to meet specific customer needs to support economic operation of the existing distribution grid, or both. Reliability of service and power quality are enhanced by the proximity to the customer and efficiency is often boosted in on-site applications by using the heat from power generation. While central power systems remain critical to the nation's energy supply, their flexibility is limited. Large power generation facilities are capital-intensive undertakings that require an immense transmission and distribution grid to move the power [20]. DG complements central power by providing a relatively low capital cost response to incremental jumps in power demand. It avoids transmission and distribution capacity upgrades by siting the power where it is most needed and by having the flexibility to send power back into the grid when needed.

In the literature, a large number of terms and definitions are used in relation to DG. For example, Anglo-American countries often use the term ‘embedded generation’, North American countries use the term ‘dispersed generation’, and in Europe and parts of Asia, the term ‘decentralized generation’ is applied for the same type of generation. Moreover, in regards to the rating of DG power units, the following different definitions are currently used:

* The electric power research institute defines DG as generation from “a few kilo-watts up to 50 MW”.
* According to the gas research institute, DG is “typically between 25 kW and 25 MW”.
* Preston and Rastler define the size as “ranging from a few kilowatts to over 100 MW”.
* Cardell defines DG as generation “between 500 kW and 1 MW”.
* The international conference on large high voltage electric systems defines DG as “smaller than 50–100 MW”.

Other definitions of DG include some or all of the following [9]:

* Any qualifying facilities under the public utility regulatory policies act of 1978 (PURPA).
* Any generation interconnected with distribution facilities.
* Commercial emergency and standby diesel generators installed, (i.e., hospitals and hotels).
* Residential standby generators sold at hardware stores.
* Generators installed by utility at a substation for voltage support or other reliability purposes.
* Any on-site generation with less than “X” kW or MW of capacity. “X” ranges everywhere from 10 kW to 50 MW.
* Generation facilities located at or near a load center.
* Demand side management (DSM), energy efficiency and other tools for reducing energy usage on the consumer’s side of the meter. The alternative to this definition would be to abandon the term “DG” completely and use instead “distributed resources (DR)” or “distributed energy resources (DER)”.

### Types of DGs

DG is referred to small generators, starting from a few kWs up to 10 MW, whether connected to the utility grid or used as stand-alone at an isolated site. Normally small DGs, in the 5-250 kW range serve households to large buildings (either in isolated or grid-connected configuration). In grid-connected configuration, DGs with larger capacities are managed by a utility or an independent power producer (IPP). They are located at strategic points, normally at the distribution level, near load centers, and used for such purposes as capacity support, voltage support and regulation, and line loss reduction. DG technologies can be categorized to renewable and nonrenewable DGs [21]. DGs have many different types ranging from conventional fossil fuel based combustion engines to the renewable energy including wind, photovoltaic cells, micro-turbines, small hydro turbines, combined heat and power (CHP) or hybrid.

### Applications of DGs

The main applications for DG so far tend to fall into five main categories [20]:

* Standby power.
* Combined heat and power.
* Peak shaving.
* Grid support.
* Stand alone.

Standby power is used for customers that cannot tolerate interruption of service for either public health and safety reasons, or where outage costs are unacceptably high. Since most outages occur as a result of storm or accident related transmission and distribution system breakdown, on-site standby generators are installed at locations such as hospitals, water pumping stations and electronic dependent manufacturing facilities

Combined heat and power applications make use of the heat from the process of generating electricity, increasing the efficiency of the fuel use. Most power generation technologies create a great deal of heat. If the generating facility is located at or near a customer's site, that heat can be used for combined heat and power (CHP) or cogeneration applications.

Power costs can fluctuate hour to hour depending on demand and generation availability. These hourly variations are converted into seasonal and daily time-of-use rate categories such as on-peak, off-peak, or shoulder rates. Customer use of DG during relatively high-cost on-peak periods is called peak shaving. Peak shaving benefits the energy supplier as well, when energy costs approach energy prices.

The transmission and distribution grid is an integrated network of generation, high voltage transmission, substations and lower-voltage local distribution. Placing DG at strategic points on the grid to make grid support can assure the grid's performance and eliminate the need for expensive upgrades.

Stand-alone DG serves the customer but is not connected to the grid, either by choice or by circumstance. Some of these applications are in remote areas, where the cost of connecting to the grid is cost prohibitive. Such applications include users that require stringent control of the quality of their electric power such as computer chip manufacturers.

## Capacitor Banks

In power systems, the reactive power compensation is provided locally at all voltage levels using fixed capacitors, switched capacitors, substation capacitor banks, or static VAR compensators. Whatever the nature of the compensation, capacitors are the common elements in all the devices. The power factor correction approach using capacitor banks has been employed for the past several decades. The capacitor banks used for power factor correction include fuses, circuit breakers (CBs), protective relaying, surge arresters and various mounting approaches. Capacitorbanks are important in power factor correction. Series capacitors are vital to improving the performance of long-distance transmission [8].

Power factor correction is the main application for capacitor banks in the power system. The advantage of improved power factor is reduced line and transformer losses, improved voltage profile, reduced maximum demand and improved power quality. The capacitor banks are installed in a distribution system on pole-mounted racks, substation banks, and high voltage (HV) or extra-high voltage (EHV) units for bulk power applications. In industrial systems, the power factor correction using capacitor banks are utilized for group or individual loads. The ratings are expressed in kVAR, voltage and frequency of operation within an ambient temperature range of -40 to +46 oC [8].

### Fixed versus switched capacitor banks

Capacitor banks applied to distribution systems are generally located on the distribution lines or in the substations. The distribution capacitor banks may be in pole-mounted racks, pad mounted banks, or submersible installations. The distribution banks often include three to nine capacitor units connected in three-phase grounded wye, ungrounded wye, or in delta configuration. The distribution capacitor banks are intended for local power factor correction by supplying reactive power and minimizing the system losses. The distribution capacitor banks can be fixed or switched depending on the load conditions. The following guidelines apply:

* Fixed capacitor banks for minimum load condition.
* Switched capacitor banks for load levels above the minimum load and up to the peak load.

Usually, the fixed capacitor banks satisfy the reactive power requirements for the base load and the switched capacitor banks compensate the inductive kVAR requirements of the peak load. To obtain the best results of sizing and locations of capacitor banks, capacitor banks should be located where they produce maximum loss reduction, provide better voltage profile, and are close to the load. Usually, the capacitor banks are placed at the location of minimum power factor by measuring the voltage, current, kW, kVAR, and kVA on the feeder to determine the maximum and minimum load conditions. Many utilities prefer a power factor of 0.95.

### Benefits of capacitor banks

Using capacitor banks to supply, the leading currents required by the load relieves the generator from supplying that part of the inductive current. The system benefits due to the application of capacitor banks include [8]:

* **Reactive power support**

In distribution systems, the voltage at the load end tends to get lower due to the lack of reactive power. In such cases, local VAR support is offered using capacitor banks. In the case of long transmission lines, the reactive power available at the end of the line during peak load conditions is small and hence needs to be supplied using capacitor banks.

* **Voltage profile improvements**

The capacitor banks reduce the amount of inductive current in an electric circuit. The reduction in the line current decreases the *IR* and *IX* voltage drops, thereby improving the voltage level of the system from the capacitor banks location back to the source. In both the distribution and transmission systems, there is a need to maintain a voltage in the range 0.95–1.05 p.u.

* **Line and transformer loss reductions**

When capacitor banks are installed for power factor correction, the line current magnitude is decreased. Therefore, both I2R and I2X losses are reduced.

* **Release of power system capacity**

Power factor correction using capacitor banks provide the reactive current requirements locally and reduce the line current. Reduced line current means less kVA for transformers and feeder circuits. Therefore, the capacitor banks compensation helps to reduce the thermal overloads on transformers, transmission lines, generator and cables.

* **Savings due to reduced energy losses**

If the reactive compensation is provided in a feeder circuit, then the current through the feeder and the transformer circuit is reduced. Therefore, the cost of energy due to reduced losses will be reduced to increase the net savings.

## Modern Optimization Methods

The modern optimization methods (also called nontraditional optimization methods) have emerged as powerful and popular methods for solving complex engineering optimization problems in recent years. These methods are simulated annealing, evolutionary programming (EP), Tabu search (TS), Neural-network based methods, genetic algorithm (GA), differential evolution (DE) algorithm, particle swarm optimization (PSO) technique, seeker optimization algorithm (SOA), ant colony optimization (ACO) algorithm and Archimedes Optimization Algorithm (AOA). Most of these methods are labeled on certain characteristics and behavior of biological, molecular, swarm of insects and neurobiological systems. These new meta-heuristic tools have been combined among themselves and with knowledge elements, as well as with more traditional approaches such as statistical analysis to solve extremely challenging problems.

## Archimedes Optimization Algorithm

### Introduction to AOA

Bat algorithm (BA) is based on the behavior of real bats that are the only mammals that can fly. Most of bats especially micro bats use a nature type of sound navigation and ranging (SONAR) called echolocation to communicate, detect the objects such as prey and background obstacles surrounding them and sense the distance to their prey even in the darkness. Bats are capable of emitting a loud with pulse emission rate of sound with specified frequency in the surrounding environment and receive the echo after striking the objects. Therefore, they compute the distance up to the object. Moreover, they can distinguish the difference between prey and obstacle, in addition to the size of objects. BA was first proposed by Yang [4], while the binary version of this algorithm was first introduced by Mirjalili *et al*. [5]. The approximate rules of the echolocation characteristics based on the features of bats are presented in [6]**.**

**5.2.2 BBA mathematical model**

BBA algorithm is based on the social behavior of bats for hunting the prey. Bats fly with velocity vector *vi* at position vector *xi* with frequency vector *λi* in d-dimensional binary search space and these vectors are updated in each iteration. Therefore, the modified velocity of each bat can be calculated using the current velocity and the difference between the current position and the global best among all bats(*gbest*) multiplied by the frequency as follows [5]:

 (5.1)

where, *vik+1* and *vik* are the velocity of bat *i* at iterations *k+*1 and *k*, respectively. *xik* is the position of bat *i* at iteration *k*, *gbest* is the best solution obtained so far, and λi is the frequency of bat *i* which can be calculated as:

 (5.2)

where, λmin and λmax are the minimum and maximum limits of frequency, respectively. *β* is a random number of a uniform distribution in the range [0,1]. Bats change their positions according to the probabilistic transition rule that depends on their velocities. The probabilistic transition rule should be restricted in the range [0,1]. Therefore, the probabilistic transition rule of bat *i* at iteration *k* can be expressed as [5]:

 (5.3)

Now, the position of bat *i* at iteration *k+*1 can be flipped based on the probabilistic transition rule as [5]:

 (5.4)

where, *xik+1* and *xik* are the positions of bat *i* at iterations *k+*1 and *k*, respectively, while (*xik*)-1 is the complement of *xik* up to the maximum value. After that, the bat positions are updated based on the pulse emission rate (*ri*) and random value as:

 (5.5)

where, (*xik*)*best* is the best position of bat *i* at iteration *k*, and *rik* is the pulse emission rate of bat *i* at iteration *k*. After the global best solution is achieved, both the loudness and the pulse emission rate of bats should be updated, where the loudness should be decreased, while the pulse emission rate should be increased as follows [5]:

 (5.6)

 (5.7)

where, *Lik+1* and *Lik* are the loudness of bats at iterations *k+*1 and *k*, respectively. *rik+1* is the pulse emission rate of bats at iteration *k+*1, while *ri0* is the initial value of the pulse emission rate. *α* and *γ* are constants, where *α* lies between 0 and 1, while *γ* is greater than zero. Finally, the position vector is updated based on the procedure of random walk as follows:

 (5.8)

where, *xnew* and *xold* are the updated and old values of bats positions, respectively. *ε* is a random number in the range [-1,1] and *Lavgk* is the average loudness emitted from all bats at iteration *k***.**

**5.2.3 BBA Algorithm**

The process of BBA for solving the optimization problems can be summarized as follows:

***Step 1: Initialization***

Insert the follows:

* Insert the control variables or bat positions that represent the locations and sizes od DGs and capacitors between the minimum and maximum limits as follows:

 (5.9)

* Insert the BBA parameters, number of bats (*Nbats*), *α*, *β*, *γ*, *ε*, λmin and λmax.
* Insert the initial values of the loudness (*Li*) and the initial pulse emission rate (*ri0*). In addition, initialize the bats velocity and frequency.
* Insert the candidate buses.
* Create a search space with dimensions (*Nbats* x *Ncan*), where *Ncan* is the number of candidate buses.

***Step 2: Provide bat first position***

Each bat is positioned randomly within the reasonable range of each control variable in a search space with one bat at each position in the length of randomly distributed values.

***Step 3: Initial evaluation***

For each bat, calculate the initial value of objective function with the candidate buses in the search space as:

 (5.10)

***Step 4: Check the system constraints***

For each bat, check the system constraints in Eqs. (3.2)-(3.12) based on the values of control variables to accept the values of objective functions that correspond to the bats satisfying the system constraints.

***Step 5: Initial global best solution***

For accepted solutions after checking constraints, the initial global best solution (*gbestinit*) can be determined according to the objective function.

***Step 6: Probabilistic transition rule***

For each bat, calculate the velocity vector from Eq. (5.1). Then, each bat changes its position in the range of control variables according to the probabilistic transition rule in Eq. (5.3). The bat positions or control variables are modified as the following steps:

1. Calculate the probability using Eq. (5.3) for each bat.
2. If *Pik+1* < *rand*, the bat position (*xik+1*) is modified to be the complement of the bat position (*xik*). Otherwise, the bat position (*xik+1*) is kept as the position (*xik*).
3. Repeat the previous steps for *bat*-times.
4. Get the final form of the modified control variables.

***Step 7: Search space updating***

For each bat, the control variables can be updated using Eq. (5.5).

***Step 8: Fitness function***

After updating the search space, the objective function can be determined for each bat at iteration *k* as:

 (5.11)

***Step 8: Check the system constraints***

For each bat, check the system constraints in Eqs. (3.2)-(3.12) based on the updated control variables to accept the values of objective functions that correspond to the bats satisfying the system constraints. Therefore, the global best solution (*gbest*) at the current iteration can be obtained.

***Step 9: Global best solution***

For accepted solutions after checking constraints, the global best solution (*gbest*) at iteration *k+*1 can be determined as:

 (5.12)

***Step 10: Control variables, loudness and pulse emission rate updating***

After the optimal solution is obtained at the current iteration, the control variables, loudness and pulse emission rate are updated using Eqs. (5.6)-(5.7).

***Step 11: Check stopping criterion***

The program will be terminated when the maximum iteration is reached or the best solution is obtained.

The flow chart of the BBA to find the optimal solution is shown in Fig. 5.1

Start

*Initialization*; Insert BBA parameters, control variables, candidate lines, initialize bat position, velocity, frequency, pulse emission rate, the loudness and create the search space

Check the system constraints

Determine the initial global best solution

Generate the initial position randomly of each bat

Initial evaluation process

Apply probabilistic transition rule

Search space updating

Determine the Fitness function

Check the system constraints

Determine the global best solution

Control variables, loudness and pulse emission rate updatin*g*

Check stopping

criterion?

Get the optimal solution

No

Yes

**Fig. 5.1 Flow chart of BBA**