

Optimized Allocation of Distributed Generation With Evolutionary Programming: A Review

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Abstract: *This paper discusses the optimal allocation of renewable DG units in a radial distribution network with an evolutionary programming based algorithm. A sensitivity analysis method, which is used to select the locations from the priority list to locate the DG units, is applied to decrease the computational burden and search space. For evolutionary programming based algorithm, to produce the population ensuring the possibility of every individual, an index based method has been discussed which decreases the calculation time. Optimal location of DG units considerably decreases the losses and improves the voltage profile.*

I. INTRODUCTION

Distributed generation integrated with distribution network has several benefits such as economical and technical benefits to both customers and utilities. Moreover, including a distributed generation may not always enhance the system performance. DG may have negative affect on distribution network which depends on penetration level, location and size. Hence, for a distribution network, optimal allocation of DG units plays an important role.

In distribution systems, for placement of DG units, many issues, such as minimization of investment, reduction of harmonic pollution, reduction of system power loss, maximization of DG capacity and voltage profile improvement etc. is aimed in the single or multi objective problem formulations. Various optimization techniques, like Decision Theory approach, Classical Second Order method, genetic algorithm (GA) technique, Hereford Ranch Algorithm, analytical approach, mixed integer nonlinear programming, Primal-Dual Interior-Point method, evolutionary programming (EP) technique, trade-off method, linear programming technique, heuristic approaches and Tabu Search approach has been used for the optimization problems of distributed generation allocation.

Distributed generation is emerging as a new concept of Generating and providing electrical power in heart of power system, which depends on the installation and operation of clean and compact power generating units near the consume site of meter or the distribution network [1]. DG units are also called embedded generation, decentralised generation and dispersed generation and are the compact generation plants which are connected directly to the load end. From the last decade, the renewable energy generation is internationally encouraged and aims at reducing the emissions of green house gas and global warming by increasing the portion of renewable energy sources and extremely efficient micro-combined heat and power units for electric power generation. Some environmental advantages of DG are,

- Reduces operational cost on peak hours
- Energy resources are diversified
- Lower the transmission and distribution losses and cost
- Contribute in the application of energy policies
- Service quality to the customers and highly increased[2]

Surveying about distributed generation, this paper discuss about the various DG technologies, applications, benefits and issues related. Moreover, adding to the topics impact of distributed generation will be reviewed.

II. DG TECHNOLOGIES

DGs are classified into categories according to the technological and constructional points of view. These types of DGs are considered as options to be compared and chosen according to the kind of situation [1].

The two-levels on which the distributed generation takes place are the local level and the end point level. The site specific DG renewable technologies like wind turbines, solar systems, some hydro thermal plants and geothermal energy production are the local level power generation plants. These DGs are less centralised and smaller than the traditional model plants. They are more reliable, energy and cost efficient. The larger central model plants produce more environmentally disrupting and damaging energy than the local level DG producers as they often take into account the local context.

With similar effects, many of these same technologies can be applied to the individual energy consumer at the end-point level. Modular internal combustion engine is one of the DG technologies frequently used by end point users. At end point level the DG technologies serve as small contributors to power grids or can be operated as isolated islands of electrical power generation. Almost every study confirms that without major structural changes, the DG penetration up to a level of 10 to 15% of maximum load can be easily absorbed by the electricity network. The level of penetration in many electricity networks is still below this limit, but this will change. Some significant DGs are categorised with their ratings as follows: Micro distribution generation ($\sim 1W < 5kW$), Small distribution generation ($5kW < 5MW$), Medium distribution generation ($5MW < 50kW$) and Large distribution generation ($50MW < 300MW$).

They are compared on the basis of several parameters such as installation and maintenance cost, fuel used, module/size, overall and electrical efficiency, green power, reliability and power quality. They are also characterised as non renewable energy and renewable energy based technologies.

A. Applications

The applications of DGs depend on the load requirements and different distributed generations are used to fulfil the requirements of wide range of applications, which affects the kind of DGs used. Some of the applications are listed below:

- 1) *Base load:* Utility owned DGs enhance the system voltage profile, improve system power quality and reduce power losses by supporting the grid and provide part of the main required power which is used as a base load.
- 2) *Rural and remote applications:* DG can provide the required power with stand alone remote applications which include communication, lighting, small industrial process, cooling and heating. Moreover, the system voltage at rural applications with sensitive loads connected to the grid are supported and regulated by the DG.
- 3) *Stand alone:* The isolated areas having geographical obstacles, which is costly to be connected to the grid use DGs as power provider.
- 4) *Standby:* Sensitive loads such as hospitals and process industries, uses DG as a standby to supply the required power during grid outages.
- 5) *Peak load shaving:* The electricity cost for large industrial customers who used to pay time of use rates (TOU) can be reduced by using DG by supplying some loads at peak periods. According to the load demand curve and the corresponding available generation, the electric power cost varies, at the same time.
- 6) *Providing combined heat and power (CHP):* The heat which is produced from converting fuel into electric power process is used for various applications in process industries, large commercial areas and hospitals. DGs have a high overall efficiency as they are providing CHP as a cogeneration [1].

B. DG Benefits

There are economical, technical and environmental benefits of employing a DG on already existing distribution network and they are interrelated. Some of them have technical flavours while all of the others have valuable benefits in terms of money [4]. Many DG units utilize renewable energy sources based on CHP and hence facilitate cleaner power production. Renewable energy source DGs increase overall efficiency and lower green house emissions. Some benefits are listed below.

1) *Environmental Benefits*

Recent study confirms that widespread use of DGs reduces emissions: Danish power systems observed that in 1998-2001, widespread use of DGs reduced the emissions by 30% and British analysis reported that in 1999, the use of domestic CHP technologies reduced the carbon dioxide emissions by 41%. Academics and environmentalists suggest that distributed generation can provide secondary benefits to society as compared to large centralized power plants. Hence, diversity of energy sources can be increased using distributed generation.

Some of the DGs such as fuel cells, micro turbines and some internal combustion units use natural gas, most of which is produced in United States. Other DGs such as renewable energy technologies like, hydro electric turbines, Solar PV panels and wind turbines, consume no fossil fuels. As the diversity increases, it helps in insulating the economy from interruptions, price shocks and fuel shortages. Adding to these benefits, the environmental advantages are low emission, more green power and low noise. Consumers who are more environmentally inclined, they may purchase these DGs for these benefits, even if they pay slight premium for green power compared to the grid power [3].

2) *Technical benefits*

Technical benefits include various issues including good voltage profile, improved continuity and reliability, peak load shaving, reduced system losses and removal of some power quality problems. The well developed power systems are losing 10% of the total generation in losses, while some of the developing countries losing 15% to 20% in these losses. So, reduction of losses can be of interest to some utilities in these countries. Also, the size and placement of DG are two main factors in loss reduction. The main technical benefits are:

- Improved power quality
- Increased overall efficiency
- Reduced line losses
- Relieved transmission and distribution congestion
- Enhanced system reliability and security
- Voltage profile improvement [4]

3) *Economical Benefits*

Economically DGs benefits in saving transmission and distribution cost, saving world fuel and reducing whole sale electricity price. The main economical benefits are:

- Lower operating costs due to peak shaving
- Reduced fuel costs due to overall efficiency
- Enhanced productivity
- Deferred investments for upgrades facility
- Increased security for critical loads
- Reduced reserve requirements and associated costs
- Reduced health care costs due to improved environment
- Reduced operation and maintenance costs of some DGs[4]

C. *DG issues and limitations*

Researches will need to tackle these challenges when DGs are incorporated on a large scale:

- 1) The power electronics used to control the SPV in wind technologies face power quality issues.
- 2) The increase in the fault currents which depends on the location of DGs
- 3) Using inverters for interconnection, injection of harmonics into the system by asynchronous DG sources.
- 4) Protection schemes: The major part of the distribution networks are in radial form, most of them at split rings. The protection system is designed accordingly as it generates unidirectional flow patterns.
- 5) System frequency: Due to unbalance between supply and demand, deviations from the system nominal frequencies are caused.
- 6) Reverse power flow: As a consequence of connecting distributed generation in the system causing malfunctions of protection circuits as they are configured at present.

- 7) Isolating protection: This is an important condition in which a portion of the utility system that contains both distributed resources and load, while being isolated from remainder of the utility system remains energized. It is important to place protective equipments such as transfer switches and relays (mechanical or electronic), as a DG may be feeding a short circuit and hence generating the possibility of fire or energizing of any segment of the network. If the workers are not prior informed or advised of the possibility then it may be proved fatal to them.
- 8) High cost of generation if renewable energy resources are used as these technologies are not much matured.
- 9) Stability issues
- 10) Reactive power: Many distributed generation technologies do not supply reactive power to the grid as they are asynchronous generators.
- 11) Voltage levels: The magnitude of the power flow changes as the installed DG changes the voltage profile of the distribution network. Mostly, voltage profile tends to increase, which is not an issue in congested networks with low voltage problems, as would be in the contrary.

D. Impact of the distributed generation

It is assumed for the design of distribution system that the electric power flows from the power system to the load. Hence, if a reverse flow from generators occurs or output fluctuates on the grid because of the DG, there is likely to be some influence on the overall distribution system in terms of voltage profile, power quality, power losses, reliability or protection and safety. Some of the potential impacts of distributed generation is described below [6].

1) Power losses

Due to the closeness of DGs to the load centres, it causes a significant impact in electric losses. Distributed generation units should be located in places where they provide maximum reduction of losses. This process is similar to capacitor allocation to reduce losses. The principal difference is that the capacitor banks only have impact in the reactive power flow, while the DG units cause impact on both active and reactive power. In feeders with high losses, a small amount of DG strategically allocated with 10% to 20% of the feeder load, could cause a significant reduction of losses.[7]

- For a certain DG capacity there is a location in the system so that if we connect at that location power losses are minimum in comparison than the DG is connected at any other point.
- When a DG is connected in a system power losses are reduced.
- Optimum location, that location where the losses are minimum.

2) Reliability

It is important to maintain and plan reliable power systems as, power outages and cost of interruptions can have severe economic impact on its consumers and utility. The goal of power system is to supply electricity to its consumers reliably and economically [7][8]. Since distribution outages are less costly and more localized than transmission and generation level outages, evaluation techniques and reliability analysis at the distribution level are less developed than at the generation level. According to the analysis of the consumer outage data of utilities has shown that the largest individual contribution for unavailability off supply comes from failure of distribution system. To increase the reliability of power supply is one of the major purposes of integrating distributed generation to distribution system [8]. DG can be used during peak load periods in order to avoid additional charges. DG can also be used as a main supply or a back-up system.

3) Voltage profile

The distribution systems are usually regulated by the use of voltage regulator or capacitors on feeders and through tap changing at substation transformers. Power flows from substation to the loads is assumed in this form of voltage regulation. Distributed generation introduces meshed power that may interfere with traditionally used regulation practices [7][8][9]. By enabling reactive compensation for voltage control, contributing for frequency regulation, reducing the losses and acting as spinning reserve in main system fault cases, the DG installation can have positive impacts in the distribution system[10][11]. On the other hand, the inappropriate DG allocation can cause over voltages or low voltages in the network as, the control of voltage regulation is usually based on radial power flows. Over voltage and under voltage conditions can arise because of the incompatibility of DG with the voltage regulation in radial power flows.

III. OBJECTIVE FUNCTION

Renewable distributed generation implementation in distribution systems grabbed the attention because of the uncertainties related with the use conventional energy sources and the environmental concerns.

Generally, to maximize the benefits in a planning problem means while maintaining the system performance within acceptable limits while minimizing the cost. Cost includes following.

- Capital cost: The responsibility of DG units capital cost is only of the customer.
- Running cost (maintenance and operation cost): With the capital cost, maintenance and operation is also customer's responsibilities only.
- Due to interruption, the cost of unserved energy (increasing the system reliability): The cost which is based on the current practise of installing DG units, represents the impact of renewable DG units on the reliability of the system.
- Feeder power losses: For planning problems, the network losses are main consideration for the following reasons:
 - (i) DG units can reduces losses and unload lines, overheating of feeders and excessive losses can occur due to improper allocation of DG units by reverse power flows from larger unit.
 - (ii) Due to minimization of power losses of the system the impact is positive on voltage profile improvement, relieving the feeders and reducing the voltage drop and has other economical and environmental benefits.

Hence, minimizing the annual energy losses of the distribution system is the aim of the anticipated planning problem for all possible operating conditions, without violating system limitations.

IV. MATHEMATICAL MODELLING

This part explains both of the renewable resources and load generation modelling.

A. Sensitivity Analysis

The proper location of DG units in the distribution network is a combinatorial problem of optimization. Even for a small distribution networks, it is computationally difficult to search for the best combination between all the possible combinations for DG units location. To compact the search space, a suitable sensitivity analysis technique can be used reducing the number of candidate locations. Firstly, the proposed method calculated the active power loss sensitivity with respect to injections of reactive and active power in the distribution network which is to identify the most suitable sensitive/candidate locations for DG placements. Due to the injected power, the sensitivity of active power loss i.e., P_L of the system is defined as

$$\text{Sensitivity of } P_L = \frac{\partial P_L}{\partial S} = \frac{P_L^{S+\Delta S} - P_L^S}{\Delta S} \quad (1)$$

where,

S is the injected active power or reactive power, ΔS is the increment in S , $P_L^{S+\Delta S}$ represents the value of P_L with injected power $S + \Delta S$ and P_L^S represent the value of P_L with injected power S . After the sensitivity of active power loss with respect to reactive power or active power is calculated, then the buses are arranged in the priority order according to the descending order of the sensitivity values obtained and a candidate buses are selected according to the desirable number of buses as the possible candidates for DG units placements.

B. Solar Irradiance Modelling

The data of irradiance generally have a bimodal distribution function for a typical day in each season for the same hour. Two groups are formed by dividing the irradiance data into two and each having a unimodal distribution function. Hence, a Beta probability density function is used for each unimodal to explain the random phenomenon of the data of irradiance as following:

$$f_b(s) = \begin{cases} \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} * s^{(\alpha-1)} * (1-s)^{(\beta-1)}, & \text{for } 0 \leq s \leq 1, \alpha \geq 0, \beta \geq 0 \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where s denotes the solar irradiance (kW/m^2), $f_b(s)$ is the Beta distribution function of s with parameters as α, β .

The random variable has standard deviation (σ) and mean (μ) and is used to calculate the Beta distribution function parameters which are used as follows:

$$\beta = (1 - \mu) * \left(\frac{\mu * (1 + \mu)}{\sigma^2} - 1 \right) \quad (3)$$

$$\alpha = \frac{\mu * \beta}{1 - \mu} \quad (4)$$

C. Wind Speed Modelling

Weibull probability density function ($f_w(v)$) is often recommended as a satisfactory expression for behavioural modelling of speed of wind. It is based on a comparison of profiles of speed of wind estimated with Weibull pdf, especially for $k = 2$ and actual speed of wind at various sites:

$$f_w(v) = \frac{k}{c} \left(\frac{v}{c} \right)^{k-1} \exp \left[- \left(\frac{v}{c} \right)^k \right] \quad (5)$$

Where c denotes the scale index and k is the shape index. When $k = 2$, the probability density function is called a Rayleigh pdf ($f_r(v)$). This pdf imitates most of the wind speed profiles:

$$f_r(v) = \left(\frac{2v}{c^2} \right) \exp \left[- \left(\frac{v}{c} \right)^2 \right] \quad (6)$$

The scaling index of Rayleigh's can be calculated using following acceptable approximation:

$$c \approx 1.128v_m$$

V. STATE SELECTION

In the planning formulation, the output power of wind and solar based DG units is incorporated as multistate variables. The continuous probability density function of each DG unit is divided into periods (states) and in every state the wind speed and solar irradiance are kept within limits. The number of periods for the Rayleigh and Beta distributions is cautiously selected as the large number of states increases the problem's complexity and small number affects the accuracy.

During any specific hour the solar irradiance probability of every state is calculated by:

$$P_s\{G_y\} = \int_{s_{y1}}^{s_{y2}} f_b(v) \cdot dv \quad (7)$$

For wind speed:

$$P_v\{G_w\} = \int_{v_{w1}}^{v_{w2}} f_r(v) \cdot dv \quad (8)$$

Where $P_s\{G_y\}$ denotes solar irradiance probability in state y , $P_v\{G_w\}$ denotes wind speed probability in state w , limits of solar irradiance of state y are s_{y1} and s_{y2} and for wind speed limits of state w are v_{w1} and v_{w2} .

VI. SOLUTION TECHNIQUE

The formulation developed for the proper allocation of DG units in the distribution network is a combinatorial problem of optimization with non-monotonic solution surfaces that means where may exist many local minima. This type of problems is not well suitably solved by classical optimization techniques. Therefore, Evolutionary Programming (EP) can be used for the solution as these algorithms are coming out as efficient approaches for different optimization, classification and search problems, regardless of complexity or nature of the problem this can find global optima at a robust and rapid convergence rate efficiently. The EP based algorithms are satisfactorily suited for real values large scale optimization and non-monotonic solution surfaces.

Evolutionary programming is similar to evolutionary strategy and GA as it is a stochastic method and artificial intelligence. For a given problem, to generate optimal solutions EP uses evolution mechanics. Using a selection scheme and mutation operator, it evolves a candidate solution of population towards the global minimum.

For the formulated problem solution the following steps are taken by using algorithm based on proposed Evolutionary Programming:

Step 1: Generating initial population

By generating individuals population, the evolutionary programming based algorithm is initiated. In the initial population, every individual represents a possible solution. Using a random uniform distribution on its upper and lower limits every individual variable is selected randomly. When the number of DG units are fixed which are to be placed then to initialize the population the following process is employed:

- 1) For every DG type, generating all the feasible alternatives of locations.
- 2) Start from one and index every alternative from a unique integer number and save its index with subsequent alternative.
- 3) Repeat above 2 steps for every DG type.
- 4) By drawing uniformly distributed random numbers among the maximum and minimum values of the indices, initialize the population subsequent to a selected DG type for its allocation alternatives as

$$IP_{ij} = \{c_j^{Min} + U_{(0,1)} \cdot (c_j^{Max} - c_j^{Min})\} \quad (9)$$

Where

IP_{ij} index for allocation alternative of the j th DG type in the i th individual of the initial population

c_j^{Min} minimum values of indices for allocation alternative of the j th DG type

c_j^{Max} maximum values of indices for allocation alternative of the j th DG type

$U_{(0,1)}$ uniformly distributed random number between 0 and 1

Round(y) Operator to round-off y towards the nearest integer

Step 2: Calculation of fitness for population

The fitness of a defined function is evaluated for every individual after generating the initial population. Let function F_{Fit}^i is the fitness of the i th individual:

$$F_{Fit}^i = F_C + P_{SV} + P_{VV} \quad (10)$$

Where

F_C Objective function

P_{SV} Total voltage magnitude violation penalty

P_{VV} Total penalty for the violation of voltage magnitude constraints

The value of P_{VV} is generated as:

$$P_{VV} = \sum_{i=1}^{N_B} P_i^V \quad (11)$$

Where

P_i^V penalty for violation of voltage magnitude at the i th bus

$$P_i^V = \begin{cases} K_V (V^{Max} - V_i^E)^2 & \text{if } V_i^E > V^{Max} \\ K_V (V_i^E - V^{Min})^2 & \text{if } V_i^E < V^{Min} \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

Here

K_V penalty weightage constant for the constraints of voltage magnitude violation.

The value of P_{SV} is generated as

$$P_{SV} = \sum_{\forall i,j, |i,j| \in S_B} P_{ij}^S \quad (13)$$

Where the P_{ij}^S is the penalty for violating line loading constraints between bus I and j branch and can be found by

$$P_{ij}^S = \begin{cases} K_s (S_{ij}^{Max} - S_{ij}^E)^2 & \text{if } S_{ij}^E > S_{ij}^{Max} \\ 0 & \text{otherwise} \end{cases} \quad (14)$$

Where K_s for the line loading constraints violation the weightage constant

Step 3: Creation of offspring population

The already existing population with the use of a mutation operator, the offspring population is created using this relation:

$$OP_{ij} = \text{Round}\{I P_{ij} + \text{NORM}(0, \sigma_{ij}^2)\} \quad (15)$$

Where

OP_{ij} is the index of the j th DG in the i th individual of offspring population for allocation alternative, $\text{NORM}(0, \sigma_{ij}^2)$ represents a mean value of zero of a Gaussian distributed random number and a standard deviation of σ_{ij} which can be calculated as

$$\sigma_{ij} = (C_j^{Max} - C_j^{Min}) \left\{ \frac{F_{Fit}^i - F_{Fit}^{Min}}{F_{Fit}^{Max} - F_{Fit}^{Min}} + e^r \right\} \quad (16)$$

Where

F_{Fit}^{Min} Minimum values of fitness function within the existing population

F_{Fit}^{Max} Maximum values of fitness function within the existing population

e Positive number slightly less than unity

r Generation/ iteration counter

The fitness for every individual in the population is calculated in a same manner as explained in step 2 after generating the offspring population.

Step 4: Competition and selection

In the first stage there is competition of every individual from offspring population and initial population which gets score after undergoing a series of tournaments with arbitrarily selected opponents. For i th individual the score s_i is calculated as:

$$S_i = \sum_{j=1}^{N_{Tour}^i} \epsilon_j \quad (17)$$

Where

N_{Tour}^i is the number of tournaments faced by i th individual which is chosen randomly. The ϵ_j is calculated by:

$$\epsilon_j = \begin{cases} 1 & \text{if } F_{Fit}^j < F_{Fit}^k \\ 0 & \text{otherwise} \end{cases} \quad (18)$$

Where F_{Fit}^j represents the fitness value of the i th individual from offspring and initial population chosen randomly.

After competing, various individuals from offspring and initial populations scores are sorted in the priority in descending order. Among them the high performers, for the next generation are selected as parents, which are equal in count to the population size. This is how one generation/iteration of the proposed evolutionary programming based algorithm.

Step 5: Stopping condition

The difference among the parent population's maximum and minimum values is calculated at the end of every iteration. The algorithm is stopped if the difference is less than a specified tolerance, else steps 3 to 5 are repeated.

The main steps of evolutionary programming based algorithm includes initialization, mutation and competition are shown with the flowchart in Fig.1.

VII. COMPARISON OF EP WITH OTHER TECHNIQUES

As the number of iterations and the calculation time taken to converge differs for various methods and for the same method changes for various runs, so each program is made to run for 10 times and the average is calculated of best fitness in each generation. The EP based method converges rapidly towards the optimal solution. On comparing various methods for the solution of already developed formulation in terms of optimal/best solution, average for convergence calculation time taken, population size and average iteration number, it is observed that EP with or without sensitivity analysis, GA and Exhaustive search method allocate the DGs on the same locations. Moreover, there is a considerable difference in the number of convergence iterations and time taken in computation.

When the EP based algorithm is taken with sensitivity analysis, this method takes 72% lesser computational time and 57% less iterations to converge as compared to the method without the same. This shows that sensitivity method technique is appropriate to decrease the burden of computation and search space without negotiating with the quality of solution.

For computational time, EP is found to be more efficient when compared to GA. This can be because of difference in selection process and generation used in these methods. In GA, the

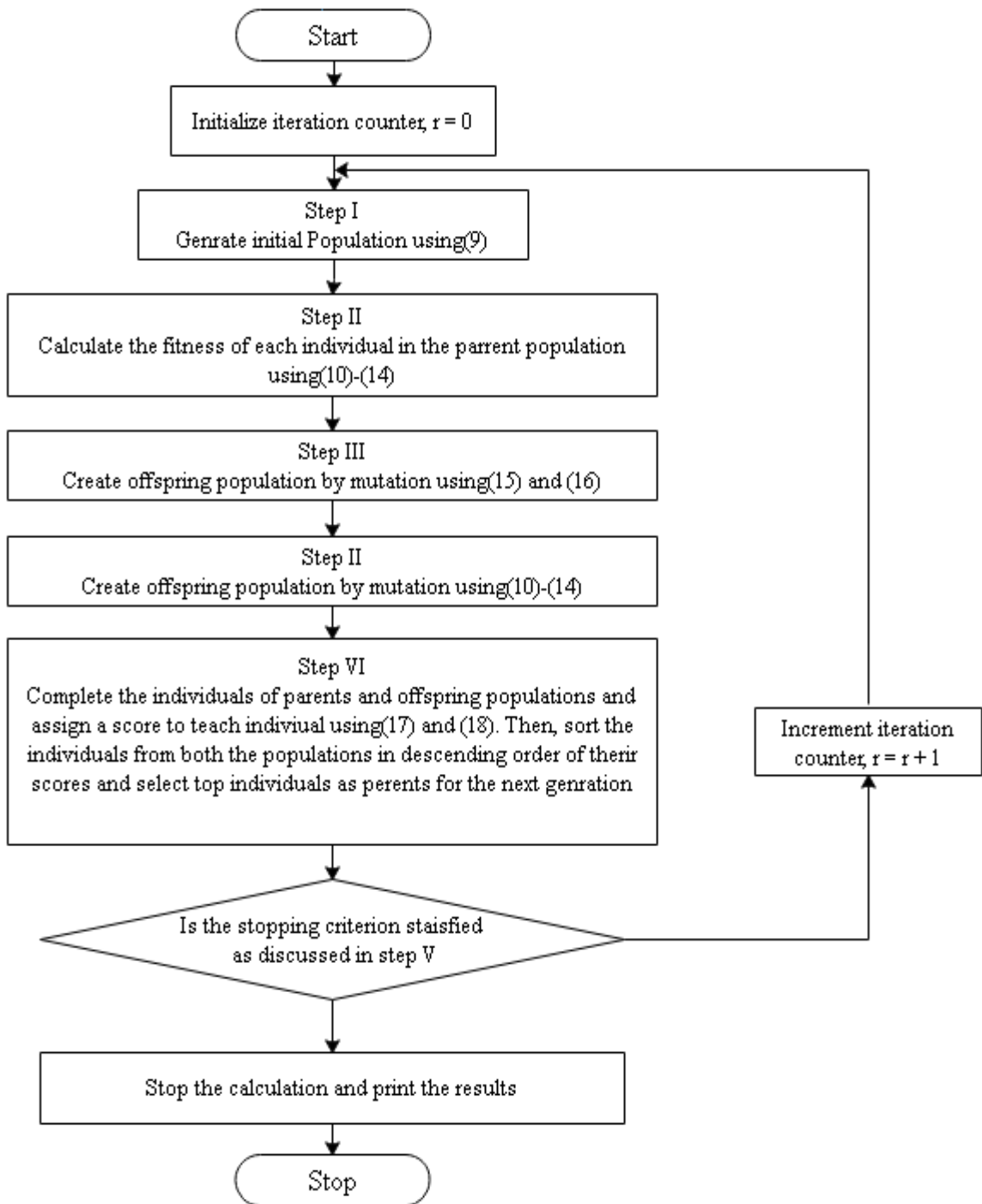


Fig.1. Flowchart for the EP technique.

process is reproduction, mutation and cross over, while in case of EP, the process is mutation and competition. Therefore, EP mainly deals real valued variables without coding and GA mainly uses binary coded variables.

VIII. CONCLUSION

This paper started with the basic definition of DG units. Further the classification of DG technologies with benefits of DG units in a distribution network was observed. The optimization of location of a DG can improve system performance by reducing active power losses. For the optimization of location, various tools are used and in this paper it is discussed that Evolutionary Programming can be used with or without sensitivity analysis technique and the former one is more efficient. When sensitivity analysis is used, to reduce the search space and computational burden, with EP, GA or exhaustive search method, then also EP is concluded as the fastest in computational time taken and takes least iterations to converge among these optimization techniques.

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