Optimal DG Allocation in a Smart Distribution Grid Using Cuckoo Search Algorithm

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ABSTRACT

In a smart distribution grid environment, the applications of Distributed Generation (DG) are widely employed. Using these applications can have both positive and negative impacts on the distribution system. The sizing and location of their installations are the issues that should be taken into consideration to gain the maximum benefit. This paper presents an application of the Cuckoo Search (CS) for the optimal sizing and siting of DG in a smart distribution power system in order to minimize real power losses by maintaining the fault level and the voltage variation within the acceptable limit. The CS is inspired by the obligate brood parasitism of some cuckoo species by putting their eggs in the nests of other species. To demonstrate the effectiveness of the proposed methodology, a simplify 9-bus radial distribution system of the Provincial Electricity Authority of Thailand (PEA) is selected for the computer simulation with DIgSILENT software to explore the benefit of the optimal DG placement and the performance of the CS.

Keywords: Distributed Generation, Cuckoo Search, Power losses, Smart Distribution Grid

1. INTRODUCTION

In recent years, the smart grid is being promoted by many governments as a way of addressing energy independence, global warming and emergency resilience issues. The DG technology using renewable resources installed in the smart distribution system is one way to achieve such problems but their installation can have both positive and negative impact on the distribution system [1] such as power flow, voltage profile, stability, continuity, reliability, short circuit level and quality of power supply for customers and electricity suppliers. The optimal location and sizing of DG is one important issue to maximize overall system efficiency and to ensure stable and reliable operation in parallel with the smart distribution system.

Various optimization techniques such as analytical method [2] and artificial intelligence approach such as hybrid genetic algorithm and simulated annealing, combined genetic algorithm [3] and particle swarm optimization [4], tabu search, non-linear and dynamic programming, differential evolution algorithm and heuristic methods [5] have been widely employed to seek the optimal location, size and operating mode for the DG interconnection. The DG application is very complex multi-objective nonlinear optimization problem. Typically, the DG problem aims at determining the optimal location to achieve optimality for some objective functions [6]-[7]. Usually, it includes maximizing the power loss reduction and minimizing the cost. Therefore, solution criteria may vary from one application to another. Also, achievement of one of the previous objectives does not guarantee satisfying the remaining ones. In addition, future changes in the solved system will alter the obtained results significantly. Therefore, more objectives and constraints are considered by the algorithm, the more data is required, which tends to add difficulty to implementation [8].

Due to the discrete nature of the allocation and sizing problem, the objective function has a number of local minima. Since the analytical methods are generally poorly suited to this type of function, only a few researches have employed these approaches.

In this paper a cuckoo search is proposed for the optimal DG allocation to improve the voltage profile which is the main criterion for the power quality enhancement and to mitigate the power losses as well as the fault level of the distribution network. The performance of the CS will be investigated by various study cases of the simplify 9-bus distribution network of the PEA.

To evaluate the result, DIgSILENT commercial software is used as a simulation tool. This software has developed in 1976 in DIgSILENT Gmbh Company of Germany. This software is directly unable to determine optimal location and sizing of DG in a distribution network. In order to add this ability, it is developed via DIgSILENT Programming Language (DPL) capability of the software.

2. PROBLEM FORMULATION

A proper DG allocation technique which minimizes distribution network losses can provide the ways to improve efficiency while reducing the utility's operating costs. Therefore, the purpose of this study is to minimize the network active power losses at peak load condition. The power loss in the system can be

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calculated by (1) as the following:

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}[\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j + P_iQ_j)] \quad (1)$$

where

$$\alpha_{ij} = \frac{rij}{V_iV_j}cos(\delta_i - \delta_j), \beta_{ij} = \frac{rij}{V_iV_j}sin(\delta_i - \delta_j)$$

P_i and Q_i are net real and reactive power injection in bus i^{th} respectively, r_{ij} is the line resistance between bus i^{th} and j^{th},V_i and δ_i are the voltage and angle at bus i^{th} respectively.

The objective of the placement approach is to minimize the total real power loss. Mathematically, the objective function can be written as:

$$Minimize \quad f_{obj} = P_L + PE \quad (2)$$

where P_L is the total power loss and PE is the total penalty function calculated from (3).

$$PE = h(V) + h(S) + h(IC) + h(IPCC) \quad (3)$$

where

$$h(V) = \sum_{i=1}^{N} h(V_i) = \begin{cases} K_V \times (V_i^{min} - V_i)^2 & ; V_i < V_i^{min} \\ 0 & ; V_i^{min} \leq V_i \leq V_i^{max} \\ K_V \times (V_i - V_i^{max})^2 & ; V_i > V_i^{max} \end{cases} \quad (4)$$

$$h(S) = \sum_{i=1}^{N_L} h(S_i) = \begin{cases} 0 & ; S_i \leq S_i^{max} \\ K_S \times (S_i - S_i^{max})^2 & ; S_i > S_i^{max} \end{cases} \quad (5)$$

$$h(IC) = \sum_{i=1}^{N} h(IC_i) = \begin{cases} 0 & ; IC_i \leq IC_i^{max} \\ K_{IC} \times (IC_i - IC_i^{max})^2 & ; IC_i > IC_i^{max} \end{cases} \quad (6)$$

where

$$IC = \frac{I_{SC,DG}}{I_{SC,Rated}} \times 100 \quad (7)$$

$$h(IPCC) = \sum_{i=1}^{N} h(IPCC_i) = \begin{cases} 0 & ; IPCC_i \leq IPCC_i^{max} \\ K_{IPCC} \times (IPCC_i - IPCC_i^{max})^2 & ; IPCC_i > IPCC_i^{max} \end{cases} \quad (8)$$

where

$$IPCC = \frac{(I_{SC,DG} - I_{SC,noDG})}{I_{SC,noDG}} \times 100 \quad (9)$$

Subject to the following constraints;

The equality constraints are the non-linear power flow equation of the distribution system. They can be written in (10) and (11) respectively.

$$P_{G_i} - P_{D_i} - \sum_{i=1}^{N} V_iV_jY_{ij}cos(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (10)$$

$$Q_{G_i} - Q_{D_i} - \sum_{i=1}^{N} V_iV_jY_{ij}sin(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (11)$$

where $j = 2, ..., N$

The inequality constraints are the voltage limits, line and transformer loading limits, real and reactive power generation and demand imposed on the distribution system are as follows:

$$P_{G_i}^{min} \leq P_{G_i} \leq P_{G_i}^{max} \quad ; \forall_i \in N_G \quad (12)$$

$$Q_{G_i}^{min} \leq Q_{G_i} \leq Q_{G_i}^{max} \quad ; \forall_i \in N_G \quad (13)$$

$$P_{DG_i}^{min} \leq P_{DG_i} \leq P_{DG_i}^{max} \quad ; \forall_i \in N_{DG} \quad (14)$$

$$Q_{DG_i}^{min} \leq Q_{DG_i} \leq Q_{DG_i}^{max} \quad ; \forall_i \in N_{DG} \quad (15)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \quad ; \forall_i \in N \quad (16)$$

$$S_i^{min} \leq S_i^{max} \quad ; \forall_i \in N_L \quad (17)$$

where

P_{G_i},P_{D_i}	are the real power generation/demand at i^{th} bus,
Q_{G_i},Q_{D_i}	are the reactive power generation/demand at i^{th} bus,
V_i,V_j	are the voltage magnitudes at the i^{th} and the j^{th} bus,
δ_i,δ_j	are the voltage angle at the i^{th} and the j^{th} bus,
Y_{ij}	is the magnitude of the ij^{th} element in the admittance matrix,
θ_{ij}	is the angle of the ij^{th} element in the admittance matrix,
$P_{G_i}^{min}$,$P_{G_i}^{max}$	are the lower and upper limits of the real power generation at the i^{th} bus,
$QG_i{}^{min}$,$Q_{G_i}^{max}$	are the lower and upper limits of the reactive power generation at the i^{th} bus,
P_{DG_i},P_{DG_i}	are the injected real and reactive power of the DG at the i^{th} bus,
$P_{DG_i}^{min}$,$P_{DG_i}^{max}$	are the lower and upper limits of the DG's real power generation at the i^{th} bus,

$Q_{DG_i}^{min}$,$Q_{DG_i}^{max}$	are the lower and upper limits of DG's reactive power generation at the i^{th} bus,
V_i^{min},V_i^{max}	are the lower and upper limits of the voltage magnitude at the i^{th} bus,
S_i,S_i^{max}	are the apparent power flow loading/loading limit of the i^{th} branch (line and transformer),
N,N_G	are the number of buses and generators,
N_L	is the number of lines/transformers,
N_{DG}	is the number of DG,
$I_{SC,DG}$	is the short circuit current with DG,
$I_{SC,noDG}$	is the short circuit current without DG,
$I_{SC,Rated}$	is the short circuit interrupting capacity,
IC_i	is the percentage of short circuit interrupting capacity (IC) at the i^{th} bus,
IC_i^{max}	is the percentage of short circuit interrupting capacity limit at the i^{th} bus,
$IPCC_i$	is the percentage of short circuit the i^{th} point of common coupling (PCC),
$IPCC_i^{max}$	is the percentage of short circuit limit at the i^{th} PCC,
K_V,K_S	is the constant of the penalty function of voltage and line/transformer loading,
K_{IC},K_{IPCC}	is the constant of the penalty function of short circuit interrupting capacity and the short circuit at PCC,
$h(V)$	is the penalty function of the voltage,
$h(S)$	is the penalty function of the line/transformer loading,
$h(IC)$	is the penalty function of the short circuit interrupting capacity,
$h(IPCC)$	is the penalty function of the short circuit at PCC.

3. CUCKOO SEARCH ALGORITHM

Cuckoo search is a meta-heuristic algorithm inspired by the obligate brood parasitism behavior of some species of a bird family called Cuckoo [9]. These kinds of birds lay their eggs in the nests of other host birds with amazing abilities such as selecting the recently spawned nests and removing existing eggs that increase hatching probability of their eggs. The host bird takes care of the eggs presuming that the eggs are its own. However, some of host birds are able to discover the eggs are not their own, they will either throw out the discovered alien eggs or build their new nests in new locations. The cuckoo breeding analogy is used for developing new design optimization algorithm. In this study the CS algorithm is as it follows:

3.1 Initialize the Cuckoo Search Algorithm Parameters

The CS parameters are set in the first step. These parameters consist of the number of nests (n), the step size parameter (α), discovering probability (Pa) and the maximum number of generation as termination criteria.

3.2 Generate Initial Nests or Eggs of Host Birds

The initial locations of the nests are specified by the set of random values assigned to each variable as:

$$nest_{i,j}^{(0)} = Round\left(x_{j,min} + rand.\left(x_{j,max} - x_{j,min}\right)\right) \quad (18)$$

where $nest_{i,j}^{(0)}$ is the initial value of the j^{th} variable for the i^{th} nest; $x_{j,min}$ and $x_{j,max}$ are the minimum and the maximum allowable values for the j^{th} variable; $rand$ is a random number in the interval [0, 1]. The $Round$ function is accomplished due to the discrete nature of the problem.

3.3 Generate New Cuckoos by Lévy Flights

All the nests except for the best one are replaced based on the quality of new cuckoo eggs produced with Lévy flights from their positions as:

$$nest_i^{(t+1)} = nest_i^{(t)} + \alpha \cdot S \cdot \left(nest_i^{(t)} - nest_{best}^{(t)}\right) \cdot r \quad (19)$$

where $nest_i^{(t)}$ is the i^{th} nest current position, α is the step size parameter; r is a random number from a standard normal distribution and $nest_{best}^{(t)}$ is the position of the best nest so far; and S is a random walk based on the Lévy flights.

The Lévy flight necessarily provides a random walk while the random step length is drawn from a Lévy distribution. One of the most efficient and yet straightforward ways of applying Lévy flights is to use the so-called Mantegna algorithm. In Mantegna's algorithm, the step length S can be calculated by the following formulas [10].

$$S = \frac{u}{|v|^{\frac{1}{\beta}}} \quad (20)$$

where β is a parameter between [1, 2] interval and considered to be 1.5; u and v are drawn from normal distribution as:

$$u \sim N\left(0, \sigma_u^2\right) \ , \ v \sim N\left(0, \sigma_v^2\right) \quad (21)$$

$$\sigma_u = \left(\frac{\Gamma(1+\beta) \cdot sin(\frac{\pi\beta}{2})}{\Gamma\left[\frac{(1+\beta)}{2}\right] \cdot \beta \cdot 2^{\frac{(\beta-1)}{2}}}\right)^{\frac{1}{\beta}} \ , \ \sigma_v = 1 \quad (22)$$

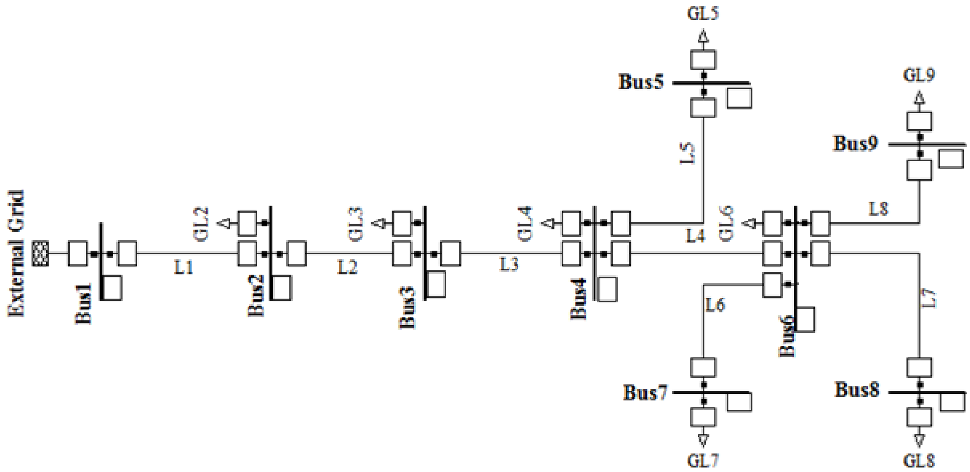

Fig.1: *Simplify 9-bus distribution test system*

3.4 Alien Eggs Discovery

The alien eggs are discovered by considering the following discovering probability matrix for each solution:

$$p_{ij} = \begin{cases} 1 & ; rand < P_a \\ 0 & ; rand \geq P_a \end{cases} \quad (23)$$

where $rand$ is a random number in [0, 1] interval and P_a is the discovering probability. Existing eggs will be replaced with a good quality of new generated ones from their current positions through random walks with step size as follow:

$$\begin{aligned} S &= rand \cdot (nests(randperm1(n), :) \\ &\quad - nests(randperm2(n), :)) \\ \text{and} \quad nest^{t+1} &= nest^{(t)} + S \cdot P \end{aligned} \quad (24)$$

where $randperm1$ and $randperm2$ are random permutation functions used for different rows permutation applied on nests matrix and P is the probability matrix

3.5 Termination Criterion

The generating new cuckoos and discovering alien eggs steps are alternatively performed until a termination criterion is satisfied.

To apply a cuckoo search optimization in the DG allocation, each nest will be represented as a set of solutions (eggs) while the eggs in the nest will be represented as the location and the capacity of DG and then seeking the best solution or the optimal siting and sizing of DG by performing the power flow and short circuit for each nests/eggs.

4. SIMULATION RESULTS

To evaluate the performance of a cuckoo search algorithm in the application of DG allocation, the simplify 9-bus distribution system of the PEA [2] which is 22-kV system as depicted in Fig.1 will be employed in this paper. It consists of one slack bus and eight load buses. The total real and reactive power demand is 7.76 MW and 3.76 MVAR and the total length of distribution line is 45 km. In the simulation, some constant parameters as tabulated in Table I will be used.

Table 1: *The Parameter Settings*

Parameters	Value
Real power limit of DG (MW)	0-8
Power factor of the DG	0.85
Voltage limit(pu)	0.95-1.05
Line loading limit (%)	80
Percentage of short circuit interuption capacity limit	85
Percentage of short circuit limit at PCC	25
Short circuit interrupting capacity (kA)	25

4.1 Result of Optimal DG Allocation

To simulate the optimal siting and sizing of DG in distribution system as shown in Fig.1, the number of nests, the discovering probability and number of iteration in cuckoo search algorithm will be set to 25, 0.25 and 100 respectively. The other parameters will be according to the data provided in Table I. Besides, the DGs have been considered to be operated in PQ mode. In the simulation, all buses of the system have be considered as candidate for installation of DGs except the first bus which is represented as in-feed of electric power from generation/transmission system.

In the study, four different cases have been explored which are no DG installation, one DG, two DGs and three DGs installation consecutively.

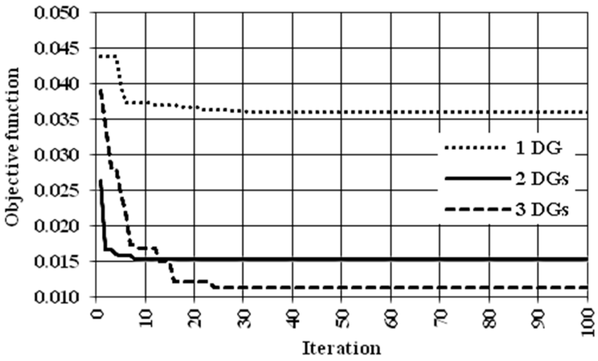

Fig.2: *Convergence of the objective function*

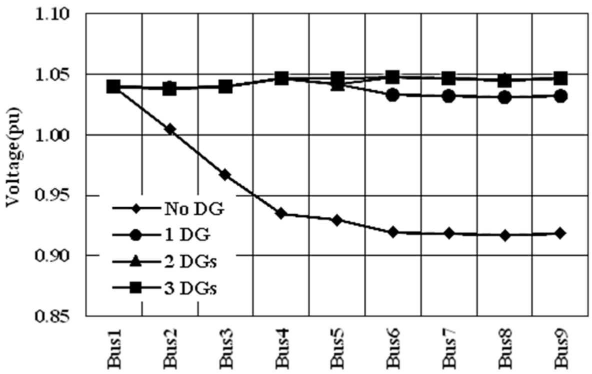

Fig.4: *Voltage profile of each case*

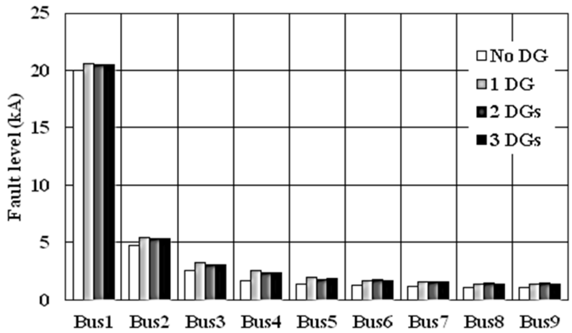

Fig.3: *Fault level at bus*

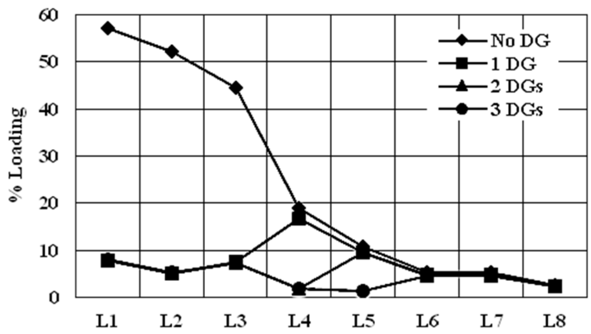

Fig.5: *Branch loading of each case*

The simulation result of optimal location and size of DG in case of no DG installation compare with the installation of one DG, two DGs and three DGs are tabulated in Table II while the convergence characteristic of the objective function by the CS algorithm of each case is illustrated in Fig.2 as well as the short circuit current, the voltage profile and the line/branch loading are depicted in Fig.3-5 respectively. In Table II, it can be seen that the power losses reduction in case of one DG, two DGs and three DGs installation compared with no DG will be 93.11% 97.06% and 97.85% respectively. In additional, the maximum capacities of DG for each case are varied between 6.424 MW and 6.538 MW which are the optimal size for

Table 2: *Optimal Sizes and Locations of DG Units*

Case	DG Location	GD Size (MW)	Total Loss (kW)	Reduced Loss (%)
No DG	-	-	523.9545	-
1 DG	Bus 6	6.538	36.1020	93.11
2 DGs	Bus 4	4.000	15.4047	97.06
	Bus 6	2.439		
3 DGs	Bus 4	2.500	11.2761	97.85
	Bus 5	2.501		
	Bus 6	2.423		

this test feeder. Fig.4 illustrates that the worst voltage profile refers to the system without DG and it can be improved by proper DG allocation such as Cases 2 and 3 which have the best voltage profile compared with other cases.

From the results as mentioned, it can be concluded that installation of three DGs at three different buses with the proper capacity will reduce the total power losses in a smart distribution system while it can maintain both the voltage profile and the fault level within the acceptable limit.

4.2 Impact of Cuckoo Parameter Setting

In this section, the performance of the CS algorithm will be investigated by using one DG installation case and adjusting the value of discovering probability to 0.05 and 0.5 while fixing the number of nests to be 25 nests. The other cases, the number of nests will be changed to 10 and 50 while setting the discovering probability to be 0.25. The convergence behaviors of both cases are presented in Fig.6 and Fig.7 respectively.

From the result show above, it can be summarized that the adjustment of the discovering probability and the number of nests do not affect the global solution of the problem. Besides, the initial convergences of each case are slightly different. It means that the convergence rate is not sensitive to the parameters

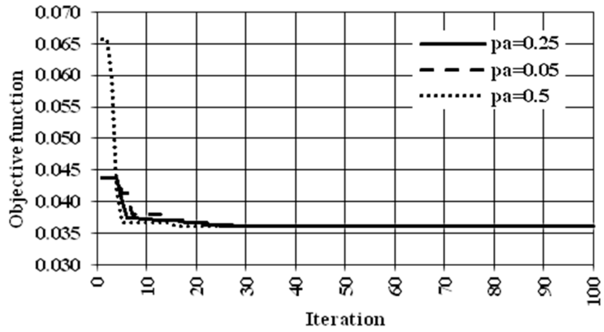

Fig.6: *Effect of adjusting discovered probability*

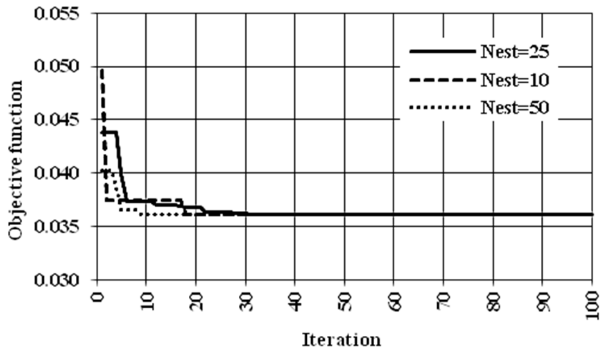

Fig.7: *Effect of changing number of nest*

used, so the fine adjustment is not needed for any given problems.

5. CONCLUSION

In this paper, the application of a cuckoo search algorithm in optimal DG allocation will be investigated. The effects of the significant parameters of the CS algorithm to optimally enhance the objective function (loss reduction, voltage profile, fault level and line loading) will be studied. The objective function is variables which are dependent on the status and position of each bus of the power network. Unlike the previous works on intelligent DG placement which all consider only a few parameters to be optimized, this study uses many possible significant parameters into account to be formulized and optimized. The CS Algorithm based method has been developed in the DIgSILENT environment to apply to a simplify 9-bus distribution network of the PEA to show the applicability of the CS algorithm. It has been shown that the potential of using the CS algorithm in power system optimization problem such as the DG allocation is viable because it needs a few parameters to be tuned, the global solution is obtained by using Levy flight and the convergence rate is not sensitive to the parameters used. Thus, this algorithm is suitable to be widely employed in the optimization problem for the future smart distribution grid.

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