

Cuckoo Search Algorithm for Integration Wind Power Generation to Meet Load Demand Growth

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Abstract—This article presents a new efficient method for optimal placement and sizing of wind power generators (WPG) in power networks with an objective of coping maximum loadability margin and minimizing reactive power loss. A new total voltage stability based on continuation power flow (CPF) theorem is used to model the problem. The method also highlights the effects of random characteristics of wind resources on loadability margin. Cuckoo search algorithm is applied to find the optimum placement and sizing of WPG since it presents several advantages of few control parameters, high solution quality and fast computational time. The experiment results of IEEE 9-bus show that the optimum location and size of WPGs are different from those considering power system loss and voltage deviation in objective function of the optimization process. A significant effect of the random characteristic of wind resource during load demand growth is revealed. The simulation results show that the CSA can be an efficient and promising method for optimal placement and sizing of WPG in power networks problem.

Keywords—*continuation power flow; Cuckoo search algorithm; loadability margin; power loss reduction; wind power; voltage stability index*

I. INTRODUCTION

With further increase in load demand, nowadays wind power generation (WPG) has attracted a special attention in the generation expansion of a modern power system. WPG can be integrated directly into distribution systems or closer to the loads fed, where the reinforcement and expansion of conventional generation is facing economic, environmental and geographical issues. Finding, closer to the loads fed, the optimum location and the best sizing of WPG provides two main advantages. The first advantage is related to the reduction of the losses (active, reactive, or both). The loss reduction impact is relatively limited by the size and location of the WPG. However, reduction of active losses will only be a few percent of the amount of energy injected; therefore, it should not be taken as basic criteria for power system expansion. Nevertheless, it could become an issue for involving different electricity markets. The second notable advantage is related to the improvement of the voltage stability margin (VSM). A continuous load increase may lead to the operation of the power system closer to its limits, this results in increasing the

likeliness of a voltage collapse occurring causing by the reactive power limits. As the penetration level of WPG increases, it will have an impact on the VSM. Because its operation depends on environmental conditions, unlike those of typical synchronous generators.

VSM is a major concern of today's power system planning and operation. VSM is defined as the distance between the stable operation point of the system and the maximum loading point. Various approaches have been proposed for identifying this margin. One of the main approaches, the continuation power flow (CPF) [1-3] has a wide range of applications [4-6]. The collapse point method [7], sequential quadratic programming (SQP) algorithm, interior point (IP) optimization method [8]. A framework analyzed QV-constraint exchange points in the maximum loadability of view of limits of capability of the generating units has been developed in [9]. A new approach to the assessment of steady-state VSMs using the P-Q-V curve has been proposed by Ching-Yin Lee et al [10]. P-V curve approach based on the CPF is a well-used method [11,12]. The P-V curve shows the maximum loadability limits of a power system. The P-V curve margin allows determining the VSM [13-17]. Many metaheuristics approach are also developed to deal with VSM. Particle swarm optimization (PSO) [18] have been adopted to find the maximum loading point of the power system. Maximum loadability limit of power system using hybrid differential evolution with PSO has been proposed in Ref [19].

In order to extract the advantages of WPGs implementation, it is necessary to optimize their size with best locations. In this context, recently, many methods and optimization algorithm have been proposed for finding an optimal WPG placement. In Ref [20], Kalman filter algorithm was used to identify optimal locations of multiple distributed generators (DGs) considering power loss. Ref [21] proposed a new power stability index and line losses based methodology for optimal placement and sizing of a DG. An efficient strategy for enhancing the loading capacity of a distribution system through DG placement considering techno-economic benefits with load growth is developed in Ref [22]. Esmaili [23] considered the optimal sizing and placement of distributed generation units for power losses reduction and voltage stability margin enhancement within flexible network

constraints. An optimal placement of dispatchable and non-dispatchable renewable DG units in distribution networks for minimizing energy loss is proposed by Hung et al [24]. In Ref [25] a new method based on the CPF technique to determine the optimal location of DG units is presented. Mahesh et al. [26] employed an accelerated particle swarm optimization (APSO) to minimize the total power loss in radial distribution system. Puppala and Chandrarao [27] used CPF method and Linear Regression to assess the voltage stability through power-voltage (P-V) curve and bus voltage sensitivity factor. Mehta et al [28] developed a new approach for selecting the best type of DG unit and its optimal location aimed to enhance the voltage stability of with simultaneous improvement in voltage profile of radial distribution network. A new approach for allocation and size evaluation of DG, based on voltage stability indicator (VSI) and feed forward artificial neural network has been developed by Kayal and Chanda [29]. Mahdad, and Srairi [30] developed a new planning strategy for solving the optimal location and sizing of multi DG, using a flexible variant based differential search (DS) algorithm. Poornazaryan et al [31] proposed an optimal approach for allocation and sizing of DG units considering voltage stability, losses and load variations through curve fitting technique.

The research presented in this article is undertaken as an upgrade to the studies mentioned above to include randomness of the wind resource in CPF. Additionally, a new method for solving optimal WPG sizing and siting problem, for coping with maximum system loading, is developed using cuckoo search algorithm (CSA). Also, CPF is exploited to identify the total voltage stability index (TVSI), subject to network and equipment constraints. The main objective of this article is to minimize the reactive power loss and improving VSM. The novelty of this article lies in the implementation of CSA for solving the complex combinatorial reconfiguration problem. CSA is chosen since it has presented several advantages such as, few control parameters, high solution quality and fast computational time. Also the novelty lies in implementing the proposed method considering randomness of the wind resource in CPF. The proposed method is tested on standard 9-IEEE test system and the results obtained are very encouraging.

II. WIND POWER GENERATION MODEL

In this article, the randomness of wind power, associated with the inherent characteristic of wind speed, is considered in the modelling of the active power output of the wind farm.

Since the wind speed is variable at each instant as so the power load, the variation of the wind power output must be included in CPF. Considering that voltage collapse is a small event, which can be occur over a minutes to hours [32], the wind speed during this time does not change significantly. Thus, the variation of the active power output of WPG takes a small variation (a range 100% to 70 % of the installed capacity).

Reactive power consumed by a wind farm is calculated using independent-Q wind farm model. Independent-Q means the reactive power of the wind farm can be fully controlled to maintain a nearly constant power factor. It could be variable wind speed wind farms, or fixed-wind speed wind farms with

SVC (Static Var Compensator) or other reactive power compensation devices.

The reactive power of the wind farm is given by [32]:

$$Q_{farm} = Q_{ind}(P_{farm}) = \frac{P_{farm}}{\cos(\varphi)} \sqrt{1 - \cos^2 \varphi} \quad (1)$$

where Q_{ind} is the reactive power consumed by the Independent-Q wind farm, P_{farm} is the active power generated and $\cos(\varphi)$ is the power factor.

III. CONTINUATION POWER FLOW TECHNIQUE

In this section, maximum system loading margin or in other words the loading factor (λ_{max}) is identified using continuation power flow (CPF) technique. CPF is widely used as a powerful tool for tracing power-voltage (P-V) curves and thereby obtaining λ_{max} [1-6].

P-V curve has been usually used for determining the crucial state of VSM and thus the computation of the maximum loadability limit of a system. The system spots its bifurcation point where the slope of the P-V curve tends to infinity, as illustrated by Fig.1.

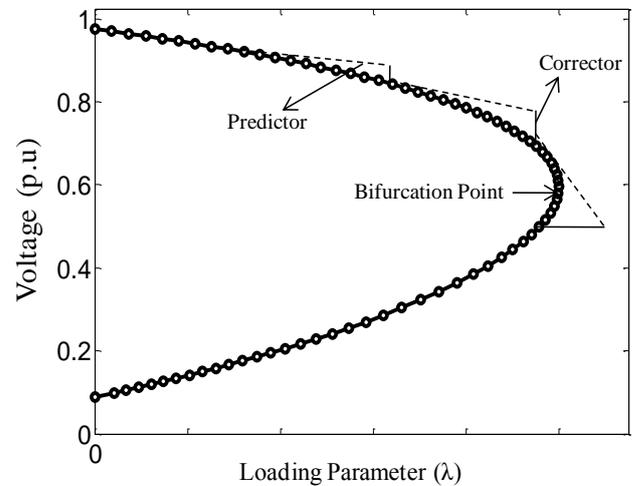


Fig. 1. P-V curve.

Continuation methods based on bifurcation theory (well-known as predictor-corrector methods), are used to trace the trajectory of a P-V curve from a stable point up to a bifurcation point or unstable point. It consists of prediction and correction steps. From a known base solution, a tangent predictor is used so as to estimate next solution for a specified pattern of load increase. The corrector step then determines the exact solution using Newton-Raphson technique employed in a conventional power flow. After that, a new prediction is made for a specified increase in load based upon the new tangent vector. Then corrector step is applied. This process goes until bifurcation point is reached.

In bifurcation theory, it is assumed that system equations depend on a set of parameters together with state variables, as follows:

$$\dot{X} = f(X, \lambda) \quad (2)$$

where X represent power system state variables and λ is loading parameter. The stability or instability properties are assessed by "slowly" varying the parameters. The parameter that is used to investigate the proximity of the system to voltage collapse is called loading parameter λ .

During the process, the active and reactive load at all buses are calculated as follows:

$$P = (1 + k_1 \lambda) P_0 \quad (3)$$

$$Q = (1 + k_2 \lambda) Q_0 \quad (4)$$

where P_0 and Q_0 are the active and reactive power at the basic operating point, and k_1 and k_2 are the control parameters to increase bus loading level.

IV. PROBLEM FORMULATION

The multi objective index (MOI) function of our optimization approach takes into account the separate total voltage stability index (TVSI), real and reactive power loss indices (ILP and ILQ). The TVSI values are maximized to enhance the loadability margin, and the values of ILP and ILQ are minimized to reduce the real and reactive power losses of the power system. The TVSI, ILP and ILQ indices are normalized between zero and one.

The MOI is built using the weighting factors (w_i) given by:

$$MOI = w_1 \cdot TVSI + w_2 \cdot ILQ + w_3 \cdot ILP \quad (5)$$

with $w_1 + w_2 + w_3 = 1$

In our optimization approach, TVSI is the first part of the MOI function with a significant weight factor w_1 of 0.6. The second part of the objective function is the ILQ receives 0.4 as weight factor (w_2) due to strong linkage between the voltage stability margin and the reactive power. The third part is the ILP takes value of 0 as weight factor (w_3) due to low impact of the DGs on reduction of active power losses on the system. During the optimization approach, various equality and inequality constraints must be satisfied.

A. Total Voltage Stability Index (TVSI)

Total voltage stability index (TVSI) is used to improve the voltage stability margin with DGs. Furthermore, it is used in the objective function for optimizing the sizing and location of DGs.

For an N-bus system, the TVSI is the ratio between the summation of the N voltage stability indexes (VSI) with DGs and without DGs. Thus, the TVSI of the system can be evaluated as follows:

$$VSI_i = \frac{V_{0_i} - V_{collapse}}{V_{0_i}} \quad (6)$$

$$TVSI = \frac{\left(\sum_{i=1}^N VSI_i \right)_{DG}}{\left(\sum_{i=1}^N VSI_i \right)} \quad (7)$$

B. Active and reactive power losses indices (ILP and ILQ)

The total active and reactive power loss indices (ILP and ILQ) are defined as:

$$ILP = \frac{P_{LDG}}{P_L} \quad (8)$$

$$ILQ = \frac{Q_{LDG}}{Q_L} \quad (9)$$

The optimal location and sizing of DGs will decrease the total network losses, which means near zero values of PLDG and QLDG.

V. CUCKOO SEARCH ALGORITHM (CSA)

Cuckoo Search (CSA) is inspired by the special behaviour of certain cuckoo species in nature. Cuckoo birds lay their eggs in the nest of other host birds. Some Cuckoo species lay their eggs in communal nests, through, they may remove others' eggs to increase the hatching probability of their eggs. Thus, if a host bird discovers that the eggs are not its own, it will either throws these alien eggs away or simply abandon the nest and builds a new nest elsewhere.

Yang and Deb [34], proposed a novel and evolutionary algorithm, named Cuckoo Search Algorithm (CSA). In order to make CSA more efficient in exploring the search space, the algorithm is enhanced by the so-called 'Lévy flight' probability density distribution.

In CSA, a nest represents a solution; the number of nest is the size of the population, while a cuckoo egg represents the new solution. In essence, the simple description of CSA can be synthesized using three idealized rules, given as follows [34]:

- Like other evolutionary algorithm, CSA starts with an initial population of cuckoos, each cuckoo chooses a nest randomly to lay their eggs and lays only one egg at a time (representing one solution);
- The best nests with high quality of eggs will be carried over to the next generations;
- If a host bird discovers that the eggs are not its own, it throws the eggs away or abandon its nest, and build a new nest in a new location. In fact, the probability that an egg laid by a cuckoo is discovered by the host bird is $p_a \oplus [0, 1]$.

Based on the above rules, the system equation for CSA is established by the combination of a local random walk and global explorative random walk, controlled by a switching parameter p_a . A random walk is a Markov chain whose next state depends only on the current state. The local random walk is written as follows [34]:

$$x_i^{t+1} = x_i^t + \alpha s \otimes H(p_a - \varepsilon) \otimes (x_j^t - x_k^t) \quad (10)$$

Using Lévy flights concept, the global explorative random walk is described in Eq. 12.

$$x_i^{t+1} = x_i^t + \alpha \otimes Levy(s, \lambda) \quad (11)$$

Here α is the step size that follows the Lévy distribution given as follows:

$$Levy(s, \lambda) = \frac{\lambda \Gamma(\lambda) \sin(\pi\lambda/2)}{\pi} \frac{1}{s^{1+\lambda}}, (s \gg s_0 \gg 0) \quad (12)$$

In order to implement the Lévy flight, a fast algorithm called Mantegna's algorithm is used to approximate the Lévy distribution [35].

VI. SIMULATION RESULTS AND DISCUSSION

The IEEE 9 node system is the example system used in this study. This system contains 9 nodes with a base kV of 345 and a base MVA of 100. The initial system loads are 315 MW and 115 MVar. It is assumed that the WPG plants are connected to the feeder on load buses 4 to 9 with a maximum capacity 60 MW in each bus. CPF is used to calculate the point of bus voltage collapse and the loadability margin. The results without WPG plants are given in Table. 1.

TABLE. 1
Load flow results without WPG

Bus	Initial load flow					CPF				
	V	Generation		Load		V	New generation level		New load level	
		Pg MW	Qg MVar	Pd MW	Qd MVar		Pg MW	Qg MVar	Pd MW	Qd MVar
1	1	71.95	24.07	-	-	1	438.75	451.57	-	-
2	1	163	14.46	-	-	1	247.9	186.59	-	-
3	1	85	-3.65	-	-	1	124.54	192.11	-	-
4	0.987	-	-	-	-	0.782	0	0	-	-
5	0.975	-	-	90	30	0.58	0	0	305.15	123.04
6	1.003	-	-	-	-	0.89	0	0	-	-
7	0.986	-	-	100	35	0.845	0	0	213.98	71.05
8	0.996	-	-	-	-	0.897	0	0	-	-
9	0.958	-	-	125	50	0.723	0	0	235.48	81.4
Total	Min=0.580	319.95	34.88	315	115	Min=0.580	811.19	830.27	754.61	275.49
Loss	PI=4.95 MW			QI=-80.12 MVar		PI=56.58 MW			QI=554.78 MVar	

From CPF the lowest voltage value (point of voltage collapse) is that obtained for bus 5 (0.580 pu) which results in a maximum load margin of 215 MW. Buses 7 and 9 have minimum load margins of 114 MW and 110 MW respectively; these low margins cause voltage collapse at high voltage values ($V_7=0.845$ pu and $V_9=0.723$ pu).

Our approach, to optimize WPG implementation, aims to minimizing the total reactive power loss and maximize the loadability simultaneously, under increasing load, taking into account different equality and inequality constraints. CSA is employed to minimize the fitness function.

The model has been developed in MATLAB to allow testing and validation of our approach. The simulation executed over 2000 iterations. The CSA parameter settings are: $p_a=0.25$, $\alpha=1$ and $\beta=3/2$.

Two represent cases of the fitness function are studied:

- Case 1: voltage margin improvement
- Case 2: reactive power loss minimization and voltage margin improvement, with $w_1=0.6$ and $w_2=0.4$.

Additionally, a third case (Case 1 random) which considers the random effect of WPG on the loadability margin is also studied by including it in the CPF. In this case, the wind power output is changed from 70% to 100% from the installed WPG determined by the optimization approach. The step

change is considered as 10 points in voltage curve.

Table 2 shows the voltage, WPG output, and new load level for the two cases.

It was found that in the base case the maximum system loadability is 803 kVA ($V_5 = 0.528$ kV). However, the WPG can host only up to 867 kVA ($V_5 = 0.525$ kV) considering voltage margin improvement as criteria, and can sustain up to 876 kVA ($V_5 = 0.87$ kV) taking reactive power loss minimization and voltage improvement simultaneously as criteria.

It was also found that considering case 2 gives better results in terms of load margin for all buses, but this requires more capacity of WPG. As can be seen, there is no big difference in the voltage margin between the two cases.

The value of the fitness function in case 2 has reduced by 10.76% in comparison with case 1 which was only 1.39 %. The evolution of the fitness functions for the two cases are illustrated in Figure.2.

The results also indicate that the total active loss of the network is reduced by nearly 9 % and that the buses voltages are improved considerably. Voltage of bus-5, bus-9, and bus-7 are reduced by 8.97%, 4.29 %, and 3.67% respectively.

The results show the importance of the fitness function in identifying the most suitable size of WPG at the appropriate location. Deployment of these WPG will eventually increase

the capability of power dispatch towards the receiving end. It is notable that WPG participation provides good reactive power support allowing enhanced network operation.

Figures 3 to 5 show the voltage collapse curves for buses 5, 7 and 9 respectively. It can be observed that the likeliness of voltage collapse is strongly decreased with the WPG. This result indicates that the WPG installation has a positive effect on improving the voltage stability and consequently will reduce the chance of power system breakdown.

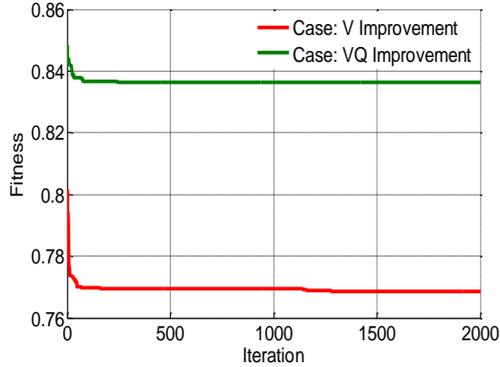


Fig. 2: fitness function evolution.

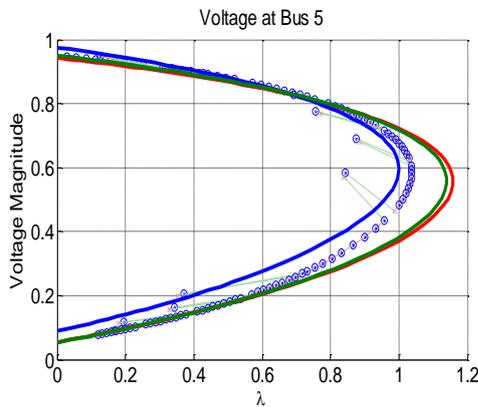


Fig. 3: voltage collapse curve of bus 5.

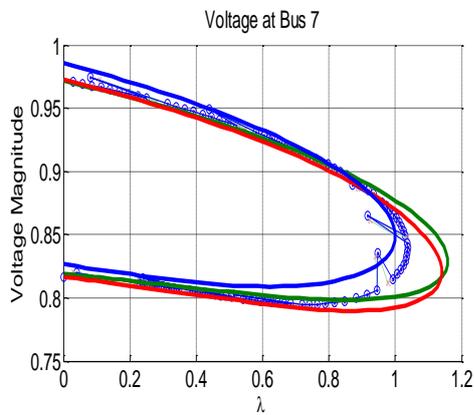


Fig. 4: voltage collapse curve of bus 7.

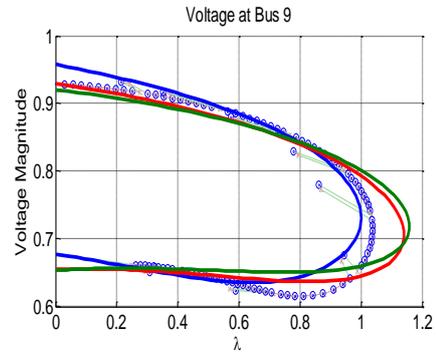


Fig. 5: Voltage collapse curve of bus 9.

I. CONCLUSIONS

The article presents a methodology for optimal location and sizing of grid-connected wind generation in electrical power networks based on continuation power flow. An independent-Q WPG model is presented in the article. Cuckoo search algorithm is used to solve the optimization problem. Simulation results for IEEE 9 node system with and without installed WPG are presented. Comparison between the results shows that adding WPG in power system will have a significant positive influence on improving voltage and loadability margins. An important problem affecting the loadability margin is the intermittency of wind power output. The result considering the randomness of wind power output shows that, during load demand growth, it will reduce the loadability margin considerably.

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