Application of Differential Evolution Algorithm to Optimal Power Flow with High Wind Energy Penetration

Linda SLIMANI and Tarek BOUKTIR

ABSTRACT: *Wind farm at windy locations is today economically competitive to conventional power generation sources. The Optimal Power Flow (OPF) problem with High Wind Penetration using Differential Evolution was explored and exploited in this paper. In order to make OPF become more reasonable, the cost of wind power generation is added into the objective function. This paper presents the enhancement of different performance parameters of power systems such as voltage profile, power flow of transmission lines and reduction of the active and reactive power losses by optimally integrate the wind farm in power systems. The modified IEEE 30 system with six thermal generating units and two wind farms is used to analyze the effect of connected wind farms on the total generation cost, the voltage profile and to active losses. Several scenarios with penetration levels from 5% to 35% and dispersion of wind generation have been investigated. The numerical results provide valuable information for system operators to determine the scheduling strategy for the power system with wind farms that would ameliorate performance parameters of power systems.*

Keywords: Optimal Power Flow, Renewable Power Sources, Wind Penetration, Dispersion of Wind Generation, Voltage Profile, Differential Evolution.

1. INTRODUCTION

The electrical energy is of vital importance to our daily life and work. With the rapid development of the global economy, energy requirements have increased remarkably, especially in emergent countries. Because of the fast consumption of non-renewable fossil fuel resources in the past several decades, the remaining available petroleum resources decrease very fast. The realization that fossil fuel resources required for the generation of energy are becoming scarce and that climate change is related to carbon emissions to the atmosphere has increased interest in energy saving and environmental protection. Among various renewable energy sources, wind power is the most rapidly growing one in Europe and the United States. Making full use of wind energy can not only reduce the environmental pollution but also bring the considerable economic benefits. The world’s wind power capacity grew by 31% in 2009, adding 37.5 GW to bring total installations up to 157.9 GW. It is predicted that by 2020, the total wind energy generation worldwide will reach 1261 GW, which is expected to supply about 12% of the total world electricity demands [1]. As a result of this scenario, high level of wind power (>30%) should be integrated into large inter-connected power systems and major issues can appear if the existing power systems are not properly redesign. Penetration levels in the electricity sector have already reached 21% in Denmark, 7% in Germany and about 12% in Spain. However, unlike thermal generator, wind power generation has a lot of intermittency and variability due to the uncertain nature of wind speed. Integrating wind farms to power grid will inevitably present a big impact on the system safety and economical operation of the system and such impact has become a hot research topic as wind power penetrations increase in power systems in recent years [2].

By the use of optimal power flow (OPF) calculation we can find out the impact of renewable energy on power systems. The OPF is an important tool that system operators require in order to operate the grid with high penetration of wind power more efficiently while maintaining all constraints within restricted limits.

In practice, when wind generators are embedded into the existing network, the output from the wind is considered as "must-take" energy, all the output of the conventional generators will be reduced to accommodate the wind output. When there is no wind generation, all the power will then be supplied from the conventional generators to meet the system demand [3].

The OPF optimises the static operating condition of a power generation-transmission system. The main benefits of optimal power flow are (i) to ensure static security of quality of service by imposing limits on generation-transmission system’s operation, (ii) to optimise reactive-power/voltage scheduling and (iii) to improve economy of operation through the full

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utilisation of the system's feasible operating range and by the accurate coordination of transmission losses in the scheduling process [4-5].

The OPF minimises an objective function representing the generation cost of the thermal and the wind units. The constraints involved are the physical laws governing the power generation-transmission systems and the operating limitations of the equipment [6-8].

As modern electrical power systems become more complex, planning, operation and control of such systems using conventional methods face increasing difficulties. Intelligent systems have been developed and applied for solving problems in such complex power systems.

In an attempt to circumvent the deficiencies of the conventional methods, several search techniques have been proposed; they are Expert System (ES), Genetic Algorithm (GA), Tabu Search (TS), Simulated Annealing (SA), Evolution Strategy (ES), Particle Swarm Optimization (PSO), etc. [9-10].

A new floating point encoded evolutionary algorithm for global optimization and named it Differential Evolution (DE) was proposed by Storn and Price [11], and since then the DE algorithm has been used in many practical cases. The original DE was modified, and many new versions proposed.

Generally DE is characterized as a simple heuristic of well-balanced mechanism with flexibility to enhance and adapt to both global and local exploration abilities. The effectiveness, efficiency and robustness of the DE algorithm are sensitive to the settings of the control parameters. The best settings for the control parameters depend on the function and requirements for consumption time and accuracy. It has gained a lot of attention in various power system applications. It is a population based method and an improved version of GA using similar operators: mutation, crossover and selection. The main difference in constructing better solutions is that GA relies on crossover while DE relies on mutation operation. The mutation operation is used as a search mechanism, which is based on the differences of randomly sampled pairs of solutions in the population. The algorithm uses selection operation to direct the search towards the prospective regions in the search space.

In this paper, a Differential Evolution method is proposed to solve the optimal power flow problem. The DE is easy to apply to the OPF problem compared with conventional methods and is able to handle continuous and discrete state variables. The objective function used is the minimization of the cost the thermal and the wind generators with different sizes. CPU times can be reduced by decomposing the optimization constraints of the power system to active constraints manipulated directly by ED, and passive constraints maintained in their soft limits using a conventional constraint load flow.

2. THE GRID INTEGRATION OF LARGE SCALE WIND GENERATORS

In the next years an elementary change in generation composition will take place as the consequence of the need to replace a lot of power stations for reasons of aging. In this situation the targeted growth of renewable and dispersed generation plays a significant role. The generation of renewable energy is co-financed by fixed prices at high levels for the different renewable power sources (RPS). These prices are independent of network level where the connections of the RPS are provided. On the other hand, the network operators are obliged by law to ensure unlimited renewable power in-feed.

In-feed of power by large wind farms is fundamentally subject to different patterns as is the case with conventional power sources such as thermal, gas turbine or hydroelectric generating plants. Three major problems need to be solved for the integration of large wind farms in transmission system: (1) Wind power output depends on meteorological conditions and may be intermittent. (2) A higher level of reserve power than before should be provided. (3) Appropriate transmission capacities must be created in order for the power to reach the load centers.

Wind power producers are entitled to transfer their production to the system through the electricity distribution or transmission company whenever the absorption of the energy by the network is "technically possible".

Wind power differs from conventional sources of energy in three main ways: the prime mover is wind, the location of resources, and the electrical machines. Controllability and availability of wind power significantly differs from thermal or hydro generation because the primary energy source cannot be stored and is uncontrollable. Wind power does not complicate very much short term balancing and all wind turbine types can be used for it, although variable speed wind turbines have better capabilities. Long term balancing is problematic. The power generated by wind turbines depends on actual value of the wind speed. When there is no wind, no power from wind turbines is available. Wind turbines complicate the long term balancing task, particularly at high wind power penetrations. The power balance of a transmission system depends substantially on the precision of weather forecasts Power output of wind generation can vary fast in a wide range, depending on weather conditions. Hence, a sufficiently large amount of controlling power from the network is required to substitute the positive or negative deviation of actual wind power in feed to the scheduled wind power amount.

3. WIND POWER MODEL

Wind model input assumptions vary from constant torque to constant power. The frequently made assumption of constant torque means any changes in shaft speed will result in a change in captured mechanical power, consequently change in power output of wind plant. A simple relationship exists relating the power generated by a wind turbine and the wind parameters [12]

In this paper, the relation between wind speed and mechanical power extracted from the wind is given as follows

$$P_g = \begin{cases} 0 & v_w \le v_{cut-in} \quad or \quad v_w \ge v_{cut-off} \\ 0.5\rho A_{wt} C_p(\beta,\lambda) v_w^3 & v_{cut-in} < v_w \le v_{rated} \\ P_{rated} & v_{rated} < v_w < v_{cut-off} \end{cases} \tag{1}$$

where P_g is the power extracted from the wind, ρ is the air density, C_p is the performance coefficient, $\lambda = \omega\, R / v_w$: is the tip speed ratio of the wind turbine while ω and R are the rotor speed and blade length, respectively , $A_{wt} = \pi R^2$ is the area covered by the wind turbine rotor, R is the radius of the rotor, v_w denotes the wind speed, β is the blade pitch angle, v_{cut-in} and $v_{cut-off}$ are the cut-in and cut-off wind speed of wind turbine, and v_{rated} is the wind speed at which the mechanical power output will be the rated power.

When v_w is higher than v_{rated} and lower than $v_{cut-off}$, with a pitch angle control system, the mechanical power output of wind turbine will keep constant as the rated power P_{rated} .

Generally, the air density, swept area of turbine, power coefficient, efficiency in equation (1) can be treated as constant for a specific site of wind plant. However, the wind speed is variable and also the wind does not blow all the time. Thus, the power generated by a wind turbine is subject to the wind speed as well as the availability of the wind at the specific location.

Currently, the most common technology used is the variable-speed Wind Turbine Generator (WTG) through the use of doubly-fed induction generators (DFIG) which is able to provide reactive power support. The major advantages of the variable speed wind generation are that they have a higher efficiency (that is, have a higher ability to capture wind energy by varying the speed of the machine with wind speed) and better power quality (that is, by storing the energy due to a gust of wind in the shaft, the power output of the unit is kept relatively constant) [13].

More exactitude equation can be derived from equation (1) inspired by [14], in which the rotor speed is controlled by setting the generator output power according to the value of wind speed as follow:

$$P_g(\omega) = \begin{cases} 0 & v_w \le v_{cut-in} \\ (\pi/2).\rho.R^2.C_p.\left(R\omega/v_1(\omega)\right).v_1(\omega)^3 & v_{cut-in} < v_w \le v_{rated} \\ \dfrac{\omega}{\omega_{rated}} P_{rated} & v_{rated} < v_w < v_{cut-off} \\ 0 & v_w \ge v_{cut-off} \end{cases} \tag{2}$$

with

$$v_1(\omega) = \frac{\omega - \omega_{cut-in}}{\omega_{rated} - \omega_{cut-in}} (v_{rated} - v_{cut-in}) + v_{cut-in} \tag{3}$$

In addition, doubly-fed induction machines can produce and/or absorb reactive power and thus regulate their apparent power factor.

Therefore, let $\cos\phi$ be power factor of wind power unit, the reactive power output of wind turbine generation Q_g can be computed as below [15].

$$Q_g = \frac{\sqrt{1-(\cos\phi)^2}}{\cos\phi} P_g \tag{4}$$

4. PROBLEM FORMULATION

The OPF problem incorporating wind power is the problem to be studied in this paper and the planned wind power combined with the power output of thermal power plant are as the variables to be optimized. Consider that, the independent system operator will be responsible for the dispatching of wind power and determine the corresponding electricity price.

The standard OPF problem can be formulated as a constrained optimisation problem as follows:

$$\begin{aligned} &\min \quad f(x) \\ &s.t. \quad g(x) = 0 \\ &\qquad\; h(x) \le 0 \end{aligned} \tag{5}$$

where *f(x)* is the objective function, *g(x)* represents the equality constraints, *h(x)* represents the inequality constraints and *x* is the vector of the control variables that can be expressed as.

The most commonly used objective in the OPF problem formulation is the minimisation of the total operation cost for producing electric power within a schedule time interval (one hour). The individual costs of thermal generating unit are assumed to be function, only, of real power generation and are represented by quadratic curves of second order. The objective function for the entire power system can then be expressed as the sum of the quadratic cost model at each generator [6-7].

$$F_{ec}(x) = \sum_{i=1}^{ng} \left(\alpha_i + \beta_i Pg_i + \gamma_i Pg_i^2 \right) \ \$/\text{h} \tag{6}$$

where α_i , β_i and γ_i are the cost coefficients of generator at bus i.

Other objective function is to minimize the Active Power Transmission Losses and/or the Voltage Deviation deviations at the load buses involving reactive power controls, while fixing active power controls.

- ✓ The active power transmission losses (P_{loss}) is given by:

$$P_{loss} = \sum_{k=1}^{N_l} g_k \left[(t_k V_i)^2 + V_j^2 - 2 t_k V_i V_j \cos\theta_{ij} \right] \quad (7)$$

where N_l is number of branch on the network, t equal =1 if the branch is a transmission line and t equal the tap ratio value if the branch is a transformer, . k is a branch with conductance g connecting the ith bus to the jth bus.

One of the important indices of power system security is the bus voltage magnitude. The voltage magnitude deviation from the desired value at each load bus must be as small as possible.

- ✓ The deviation of voltage is given as follows:

$$\Delta V = \sum_{k=1}^{N_{PQ}} \left| V_k - V_k^{des} \right| \quad (8)$$

where N_{PQ} is the number of load buses and V_k^{des} is the desired or target value of the voltage magnitude at load bus k.

- ✓ The total objective function of OPF problem

The equation of the total objective function using into account the Economic Power Dispatch (ED) objective function; active power transmission losses (P_{loss}); and the sum of the normalized violations of voltages (F_{Vi}) is as follow:

$$f = F_{ED} + \omega_l P_{loss} + \omega_V F_V \quad (9)$$

Where

$$F_V = \sum_{j=1}^{N_{PQ}} \left(\left| V_{PQj} - V_{PQj}^{\lim} \right| \right) / \left(\left| V_{PQj}^{\max} - V_{PQj}^{\min} \right| \right)$$

ω_l and ω_V constants are related to line loss and voltage deviation. These constants were found as a result of trials.

For the cas of the incertion of the wind farms in the electrical network the control vector is given by:

$$x^T = \left[Pg_1 \cdots Pg_{ng}, Pgw_1 \cdots Pgw_{nw} \right] \quad (10)$$

where *ng* is the number of standard generators & *nw* is the number of wind generators.

The essence of the optimal power flow problem resides in reducing the objective function and simultaneously satisfying the load flow equations (equality constraints) without violating the inequality constraints.

While minimising the objective function, it is necessary to make sure that the generation still supplies the load demands plus losses in transmission lines. The equality constraints are the power flow equations describing bus injected active and reactive powers of the *i* th bus.

where active and reactive power injection at bus *i* are defined in the following equation:

$$P_i = Pg_i - Pd_i = \sum_{j=1}^{nb} V_i V_j \left(g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij} \right) \quad (11)$$

$$Q_i = Qg_i - Qd_i = \sum_{j=1}^{nb} V_i V_j \left(g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij} \right) \quad (12)$$

where Qg_i is the reactive power generation at bus *i*; Pd_i, Qd_i are the real and reactive power demands at bus *i*; V_i, V_j, the voltage magnitude at bus *i,j*, respectively; θ_{ij} is the admittance angle, b_{ij} and g_{ij} are the real and imaginary part of the admittance and *nb* is the total number of buses.

The inequality constraints of the OPF reflect the limits on physical devices in the power system as well as the limits created to ensure system security.

The inequality constraints on the problem variables considered include:

- Upper and lower bounds on the active generations at generator buses $Pg_i^{min} \le Pg_i \le Pg_i^{max}$, *i = 1, ng*.
- Upper and lower bounds on the reactive power generations at generator buses $Qg_i^{min} \le Qg_i \le Qg_i^{max}$, *i = 1, ng*
- Upper and lower bounds on reactive power injection at buses with VAR compensation $Qc_i^{min} \le Qc_i \le Qc_i^{max}$, *i= 1, nc*
- Upper and lower bounds on the voltage magnitude at the all buses . $V_i^{min} \le V_i \le V_i^{max}$, *i = 1, nb*.
- Upper and lower bounds on the bus voltage phase angles $\square_i^{min} \le \square_i \le \square_i^{max}$, *i = 1, nb*.
- for secure operation, the transmission line loading S_l is restricted by its upper limit as:
- $S_{li} \le S_{li}^{max}$, *i = 1, nl*, where S_{li}, S_{li}^{max} are stand for the power of transmission line and limit of transfer capacity of transmission line and *nl* is the number of transmission lines.
- Upper and lower bounds on reactive power wind generator (continuous): $Q_w^{\min} \le Q_w \le Q_w^{\max}$

It can be seen that the generalised objective function *F* is a non-linear, the number of the equality and inequality constraints increase with the size of the power distribution systems. Applications of a conventional optimisation technique such as the gradient-based algorithms to a large power distribution system with a very non-linear objective functions and great number of constraints are not good enough to solve this problem. Because it depends on the existence of the first and the second derivatives of the objective function and on the well computing of these derivative in large search space.

5. APPLICATION OF DE ALGORITHM ON OPF PROBLEM

DE is a direct search method using operators: mutation, crossover and selection. The algorithm randomly chooses a population vector of fixed size.

During each iteration of algorithm a new population of same size is generated. It uses mutation operation as a search mechanism. This operation generates new parameter vector by adding a weighted difference vector between two population members to a third member. In order to increase the diversity of the parameter vectors, the crossover operation produces a trial vector which is a combination of a mutant vector and a parent vector. Then the selection operation directs the search toward the prospective regions in the search space. In addition, the best parameter vector is evaluated for every generation in order to keep track of the progress that is made during the minimization process. The above iterative process of mutation, crossover and selection on the population will continue until a user-specified stopping criterion, normally, the maximum number of generations or the maximum number of function evaluations allowed is met. The process is assumed to have converged if the difference between the best function values in the new and old population, and the distance between the new best point and the old best point are less than the specified respective tolerances. The other type of stopping criterion could be if the global minimum of the problem is know a-priori. Then DE will be terminated if the difference between the best function value in the new population and the known global minimum is less than the user defined tolerance level [5].

5.1. Differential Evolution optimization process

Differential Evolution uses a population P of size N^P that evolves over G generations to reach the optimal solution. Each individual Xi is a vector that contains as many parameters as the problem decision variables D.

$$P^G = \left[X_1^G, \ldots\ldots.., X_{Np}^G \right] \qquad (13)$$

$$X_i^G = \left[X_{1,i}^G, \ldots\ldots.., X_{D,i}^G \right]^T \qquad i = 1, \ldots, N_p \quad (14)$$

The population size NP is an algorithm control parameter selected by the user which remains constant throughout the optimization process. The optimization process in Differential Evolution is carried out using the three basic operations: Mutation, Crossover and Selection.

The main steps of the DE algorithms are given below:

Initialization
Evaluation
Repeat
Mutation
Crossover
Evaluation
Selection
Until (termination criteria are met)

- **Initialization**

At the early stage of DE search, i.e., t = 0, the algorithm starts by creating an initial population of NP vectors.

The problem independent variables are initialized somewhere in their feasible numerical range in every vector as follows.

$$X_{j,i}^{(0)} = X_j^{\min} + rand(0,1) \cdot \left(X_j^{\max} - X_j^{\min} \right) \qquad (15)$$

where $i = 1, \ldots.., N_P$ and $j = 1, \ldots.., D$; $X_j^{\min}$ and $X_j^{\max}$ are the lower and upper bounds of the jth decision parameter; and $rand(0,1)$ is a uniformly distributed random number within [0, 1] generated for each value of j. $X_{j,i}^{(0)}$ is the jth parameter of the ith individual of the initial population.

- **Mutation**

The mutation operator creates mutant vectors $\left(X_i^{'} \right)$ by perturbing a randomly selected vector Xa with the difference of two other randomly selected vectors Xb and Xc

$$X_i^{'(G)} = X_a^{(G)} + F\left(X_b^{(G)} - X_c^{(G)} \right) \; i = 1, \ldots, N_P \qquad (16)$$

Where Xa Xb and Xc are randomly chosen vectors among the Np population, and $a \neq b \neq c \neq i$. The scaling constant F is an algorithm control parameter used to adjust the perturbation size in the mutation operator and to improve algorithm convergence. Typical value of F is in the range of 0.4–1.0.

- **Crossover**

Two types of crossover schemes can be used by DE algorithm. These are exponential crossover and binomial crossover. Although the exponential crossover was presented in the original work of Storn and Price [4], the binomial variant is much more used in recent applications.

In exponential type, the crossover operation generates trail vectors $\left(X_i^{''} \right)$ by mixing the parameters of the mutant vectors $\left(X_i^{'} \right)$ with the target vector $\left(X_i \right)$ according to a selected probability distribution,

$$X_{j,i}^{''(G)} = \begin{cases} X_{j,i}^{'(G)}, & if \;\; \eta_j^{'} \leq C_R \;\; or \;\; j = q \\ X_{j,i}^{(G)}, & otherwise \end{cases} \qquad (17)$$

Where $i = 1, \ldots.., N_P$ and $j = 1, \ldots.., D$; q is a randomly chosen index $\in \{1, \ldots.., N_P\}$ that guarantees that the trail vector gets at least one parameter from the mutant vector; $\eta_j^{'}$ is a uniformly distributed random number within [0, 1] generated for each value of j. The crossover constant CR is an algorithm parameter that controls the diversity of the population and aids the algorithm to escape from local minima. $X_{j,i}^{(G)}, X_{j,i}^{'(G)}$ and $X_{j,i}^{''(G)}$ are the jth parameter of the ith target vector, mutant vector and trail vector at generation G, respectively.

- **Selection**

To keep the population size constant over subsequent generations, the selection process is carried out to determine which one of the child and the parent will survive in the next generation

The selection operation forms the population by choosing between the trail vectors and their predecessors (target vectors) those individuals that present a better fitness or are more optimal according to (18).

$$X_i^{(G+!)} = \begin{cases} X_i^{"(G)} & if \quad f\left(X_i^{"(G)}\right) \leq f\left(X_i^{(G)}\right) \\ X_i^{(G)} & otherwise \end{cases}, i = 1, \ldots\ldots, N_P \tag{18}$$

This process is repeated for several generations allowing individuals to improve their fitness as they explore the solution space in search of optimal values.

DE has three essential control parameters: the scaling factor (F), the crossover constant (CR) and the population size (NP). The scaling factor is a value in the range [0, 2] that controls the amount of perturbation in the mutation process. The crossover constant is a value in the range [0,1] that controls the diversity of the population. The population size determines the number of individuals in the population and provides the algorithm enough diversity to search the solution space.

Proper selection of control parameters is very important for algorithm success and performance. The optimal control parameters are problem specific. Therefore, the set of control parameters that best fit each problem have to be chosen carefully. The most common method used to select the control parameter is parameter tuning. Parameter tuning adjusts the control parameters through testing until the best settings are determined. Typically the following ranges are good initial estimates: [15]: F= [0.5, 0.6], CR= [0.75, 0.90] and NP= [3D, 8D].

In order to avoid premature convergence, F or NP should be increased, or CR should be decreased. Larger values of F result in larger perturbation and better probabilities to escape from local optima, while lower CR preserves more diversity in the population thus avoiding local optima.

5.2. DE Implementation for OPF

While applying DE to solve the OPF problem, the following issues need to be addressed.

1. Representation of the problem variables and
2. Formation of the evaluation function.

These two issues are described in this section.

5.2.1. Problem Representation

Each vector in the DE population represents a candidate solution of the given problem. The elements of that solution consist of all the optimization variables of the problem. For the case of minimization of cost the generator active powers are the optimization variables. For the reactive power planning problem under consideration, generator terminal voltages $\left(V_{gi}\right)$ the transformer tap positions (tk) and the Capacitor settings (QCi) are the optimization variables. Generator bus voltage is represented as floating point numbers, whereas the transformer tap position and reactive power generation of capacitor are represented as integers.

5.2.2. Evaluation Function

Differential evolution searches for the optimal solution by maximizing a given fitness function, and therefore an evaluation function which provides a measure of the quality of the problem solution must be provided. The objective is to minimize the total cost while satisfying all constraints. The equality constraints are satisfied by running the Newton Raphson power flow algorithm. The inequality constraints on the control variables are taken into account in the problem representation itself, and the constraints on the state variables are taken into consideration by adding a quadratic penalty function to the objective function. With the inclusion of penalty function the new objective function becomes,

$$Min\, F = f + SP + \sum_{j=1}^{N_{PQ}} VP_j + \sum_{j=1}^{N_r} QP_j + \sum_{j=1}^{N_1} LP_j \tag{19}$$

Here, SP, VP_j ,QP_j and LP_j are the penalty terms for the reference bus generator active power limit violation, load bus voltage limit violation; reactive power generation limit violation and line flow limit violation respectively. These quantities are defined by the following equations:

$$\text{SP} = \begin{cases} K_s\left(P_s - P_s^{\max}\right)^2 & if \;\; P_s > P_s^{\max} \\ K_s\left(P_s - P_s^{\min}\right)^2 & if \;\; P_s < P_s^{\min} \\ 0 & otherwise \end{cases} \tag{20}$$

$$\text{VP}_j = \begin{cases} K_v(V_j - V_j^{\max})^2 & if \;\; V_j > V_j^{\max} \\ K_v(V_j - V_j^{\min})^2 & if \;\; V_j < V_j^{\min} \\ 0 & otherwise \end{cases} \tag{21}$$

$$\text{QP}_j = \begin{cases} K_q(Q_j - Q_j^{\max})^2 & if \; Q_j > Q_j^{\max} \\ K_q(Q_j - Q_j^{\min})^2 & if \; Q_j < Q_j^{\min} \\ 0 & otherwise \end{cases} \tag{22}$$

$$\text{LP}_j = \begin{cases} K_l(L_j - L_j^{\max})^2 & if \; L_j > L_j^{\max} \\ 0 & otherwise \end{cases} \tag{23}$$

Where, $K_{s,}$ $K_{v,}$ K_q and K_l are the penalty factors. Since DE maximizes the fitness function, the minimization objective function f is transformed to a fitness function to be maximized using a large constant *k* as,

$$\text{Fitness} = k/F \tag{24}$$

6. APPLICATION STUDY

The OPF using DE method has been developed and tested with Intel Pentium Dual CPU 2220, 2.4 GHz, 2GB RAM. Consistently acceptable results were observed. Initially, several runs are done with different values of DE key parameters such as differentiation (or mutation) constant F, crossover constant CR, size of population NP, and maximum number of generations GEN which is used here as a stopping criteria. In this paper, the following values are selected as: F=0.9: CR=0.9; NP=30; GEN=50.

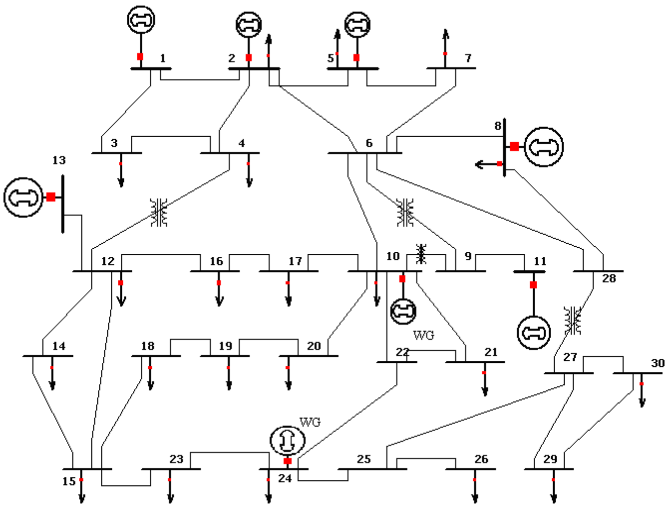

Fig. 1. IEEE 30-bus Electrical system with two Wind generator in bus10&bus 24.

The modified IEEE 30 system with six thermal generating units and two wind farms connected to bus no.10 and bus no. 24 is used to analyze the effect of connected wind farm on the total generation cost, the voltage profile and the active losses (Figure 1). The total load was 283.4 MW. Several scenarios with dispersed wind penetration levels from 5% to 35% have been investigated. The wind generators are connected to bus 10 and bus 24. The output from the wind is considered as "must-take" energy, all the output of the conventional generators will be reduced and optimized by ED to accommodate the wind output. Upper and lower active power generating limits and the unit costs of all generators of the IEEE 30-bus test system are presented in Table 1 [4].

Table 1. Power generation limits and cost coefficients for IEEE 30-bus system.

Bus	Pgmin (MW)	Pgmax (MW)	a ($/hr)	b ($/MW.hr)	c.10-4 ($/MW².hr)
1	50	200	0	2.00	37.5
2	20	80	0	1.75	175.0
5	15	50	0	1.00	625.0
8	10	35	0	3.25	83.0
11	10	30	0	3.00	250.0
13	12	40	0	3.00	250.0

In our simulation, the marginal cost of wind farm is set equal to the half of the minimum marginal cost of the existing generator in the network to reflect the subvention benefit from wind farm.

6.1. OPF results without the insertion of wind farms

The results including the generation cost, the minimum deviation and power losses in the case without the penetration of the Wind generators are tabulated in Table 2.

Table 2. Results of minimum total cost for IEEE 30-bus system by ED

Variable	Generation cost min.
Pg_{01}(MW)	175.8317
Pg_{02}(MW)	48.7671
Pg_{05}(MW)	21.1824
Pg_{08}(MW)	22.8903
Pg_{11}(MW)	12.1021
Pg_{13}(MW)	12.1936
Production cost ($/hr)	802. 7967
Power Loss (MW)	9.5672
$\sum$|Vi-Vref|	0.3142

It is found that minimized system loss and cost are 9.5672 MW and $ 802.7967 per hour respectively. It is necessary to note that only the active powers of the generators are optimized. Fig. 2 shows the typical convergence characteristics of best compromise solutions through the algorithm proceeding.

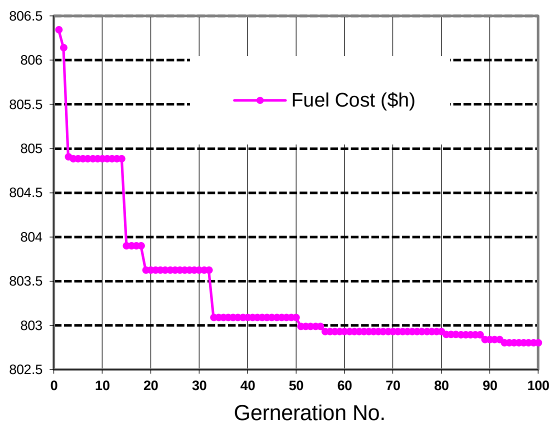

Fig. 2. Convergence characteristics of cost objective function by ED method.

6.2. Single Wind Farm site:

The wind generator is connected to bus no. 10 and bus no. 24 separately, for penetration levels from 5% to 35% with an interval of 5%. Figure 3 and 4 shows the voltage profiles when wind generation is connected to bus no. 10 and bus no. 24 respectively. These two figures show that the voltages at the load buses are all within the system limits ranging from 0.95 to 1.05 p.u. It is noticed that voltage profiles in both figures are better when wind generation is not connected into the network.

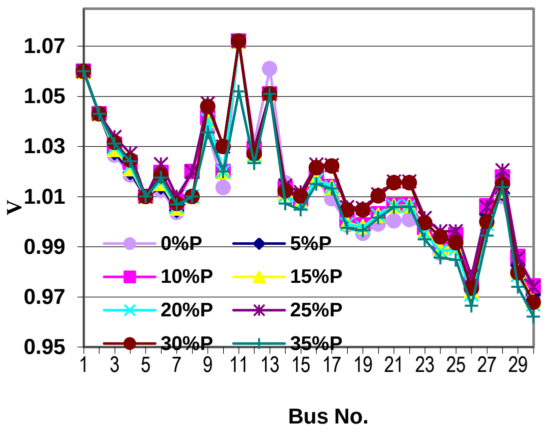

Fig. 3. Voltage profile when wind farm connected to bus 10.

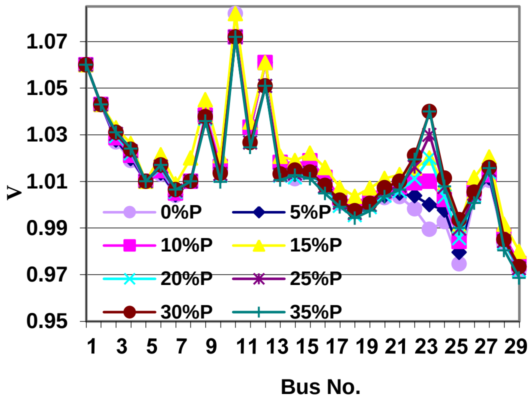

Fig. 4. Voltage profile when wind farm connected to bus 24.

The optimal active and reactive powers generated by all the generating units when wind generation is connected to bus no. 10 and bus no. 24 are shown in Figures 5, 6,7, and 8. These figures clearly represent the impacts of the locations and penetration levels of the wind generators in the transmission system.

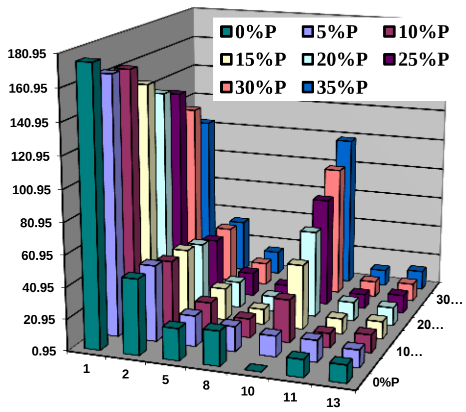

Fig. 5. The active power generation when wind farm connected to bus 10.

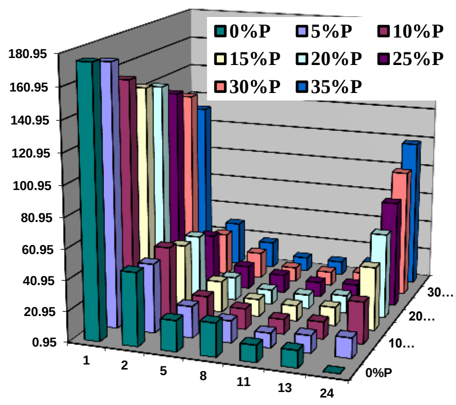

Fig. 6. The active power generation when wind farm connected to bus 24.

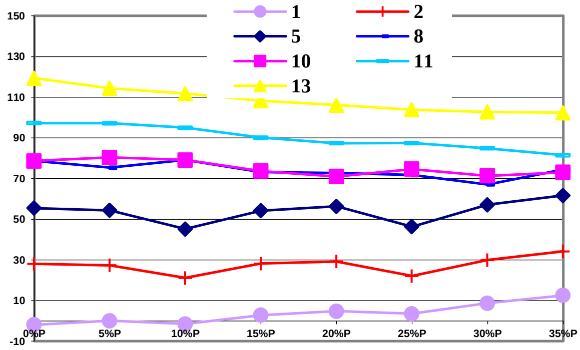

Fig. 7. The reactive power generation when wind farm connected to bus 10.

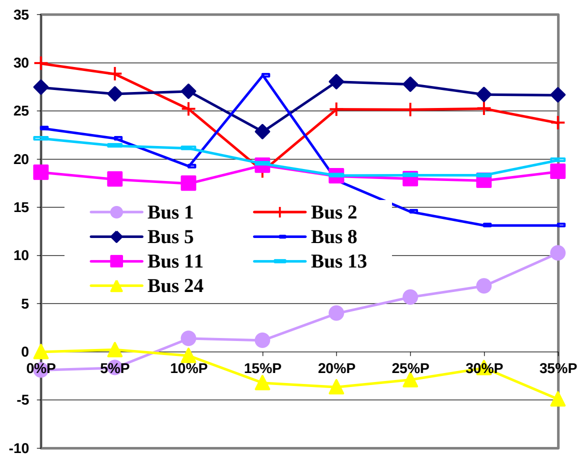

Fig. 8. The reactive power generation when wind farm connected to bus 24.

From Table 3, it can be seen that the total system cost, Power losses, and the reactive wind farm power output are different with different integrated bus. Connecting the wind farm at bus 24 will be a better option in terms reduction in the total costs and power losses for low penetrations levels (5%P, 10%P). But for high penetration level (15%P, 20%P, 25%P, 30%P and 35%P), the integration of the wind farm in the bus 24 give more better results. However, for the minimum voltage (level & phase angle) values, the results show that the bus 10 is the best location of the wind farm for all wind penetration levels. For the case of the total voltage deviation the bus 10 as wind farm location is better for the low penetration levels (5%P, 10%P & 15%P), and the bus 24 is the best location for the high penetration levels.

Table 3. Results of ABC-OPF when wind farm connected to bus 10 and bus 24 separately with different wind penetration levels

Wind farm connected to bus 10							
Wind penetration levels	5%P	10%P	15%P	20%P	25%P	30%P	35%P
QgW (Mvar)	5.0325	-0.0805	0.5167	-1.7667	2.9187	4.2562	-1.3333
Losses (MW)	8.7700	8.4891	7.7147	7.2927	7.0059	6.6657	6.4154
Cost ($hr)	759.8132	716.8071	676.4126	638.2020	599.2950	564.1949	530.9799
Vmin (p.u.)	0.9710	0.9744	0.9686	0.9670	0.9740	0.9679	0.9621
Min angle (°)	-13.4427	-13.0873	-12.0783	-11.0924	-10.4732	-9.3554	-8.3752
∑|Vi-Vref| (p.u.)	0.3304	0.3586	0.3419	0.3511	0.4342	0.411	0.3918
Wind farm connected to bus 24							
Wind penetration levels	5%P	10%P	15%P	20%P	25%P	30%P	35%P
QgW(Mvar)	0.2061	-0.4067	-3.2237	-3.6502	-2.9073	-1.663	-4.9171
Losses(MW)	6.4154	8.9467	8.1110	7.5838	8.2479	8.4413	9.0184
Cost($hr)	758.5018	716.9865	677.3283	638.5145	604.6803	570.9963	539.3447
Vmin (p.u.)	0.9621	0.9734	0.9748	0.9800	0.9718	0.9727	0.9734
Min angle (°)	-8.3752	-13.2936	-11.8204	-10.4904	-9.4471	-8.9197	-8.5013
∑|Vi-Vref| (p.u.)	0.3193	0.3468	0.455	0.3208	0.3454	0.3706	0.3521

6.3. Multiple Wind Farm location

In the multiple locations scenario, wind generation is connected to buses 10 and 24 simultaneously, and different penetration levels combinations were applied. Table 4 shows the combinations used and the overall penetration level on the system.

Table 4: Case Scenarios of Wind Dispersion on two different locations

% of Combination (G10-Low,G24-High)	% of Combination (G24-Low,G10-High)	% of Total Combination
BC (0%, 0%)	BC (0%, 0%)	0%
C1 (5%, 5%)	C1 (5%, 5%)	10%
C2 (5%, 10%)	C2 (5%, 10%)	15%
C3 (5%, 15%)	C3 (5%, 15%)	20%
C4 (10%, 10%)	C4 (10%, 10%)	20%
C5 (10%, 15%)	C5 (10%, 15%)	25%
C6 (5%, 20%)	C6 (5%, 20%)	25%
C7 (5%, 25%)	C7 (5%, 25%)	30%
C8 (10%, 20%)	C8 (10%, 20%)	30%
C9 (15%, 15%)	C9 (15%, 15%)	30%
C10 (5%, 30%)	C10 (5%, 30%)	35%
C11 (10%, 25%)	C11 (10%, 25%)	35%
C12 (15%, 20%)	C12(15%, 20%)	35%

The results obtained from the simulation where the penetration level of wind farm is low at bus 10 and high at bus 24 is shown in Figure 9. The results obtained from the simulation where the penetration level of wind farm is low at bus 24 and high at bus 10 is shown in Figure 10. The Figure 9, 10 shows that, all the bus voltages are within the operating limit for case scenario C1 to C12.

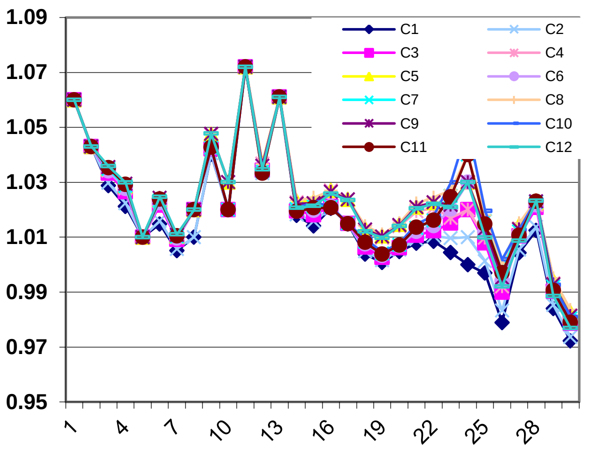

Fig. 9. Voltage profile for multiple dispersion on bus 10 and bus 24 with DG 10 Low-DG 24 High (%).

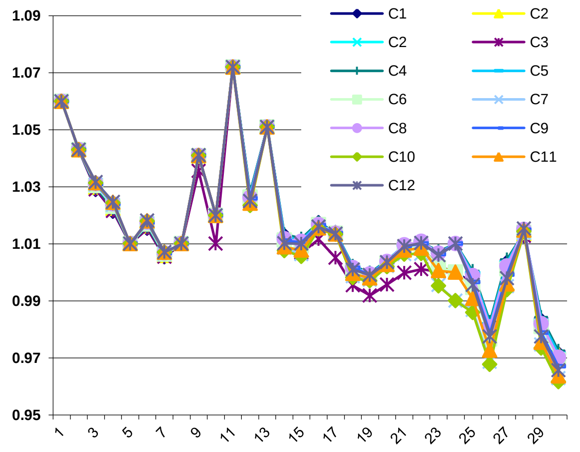

Fig. 10. Voltage profile for multiple dispersion on bus 10 and bus 24 with DG 10 High DG 24 Low (%).

The results obtained from different scenarios show that wind generation can contribute towards improving the transmission system voltage profile for some cases. Different wind penetration levels and location indeed changes the system operation.

As more wind turbines are installed, the fossil fuel plants must adjust their operations strategies in order to deal with the mismatch between actual wind energy supply and electricity demand.

The table 5 shows generation cost and loss for different wind penetration levels and location of wind farm. The generation cost and loss are found to be least due to the optimal location and mixture combination.

The results obtained from different scenarios give a signal to the utility on what penetration level and location is optimal with respect to active power losses and voltage profile, when confronted with sites having similar wind regimes. The real power losses and generation cost are lesser than both base case and single wind farm location case. Following the installation of large wind farms, the influence of wind energy on the transmission grid has grown.

Table5: Wind generation impact on active, reactive powers losses and cost

Case of Combination	G10-Low G24-High	G10-Low G24-High	G24-Low G10-High	G24-Low G10-High
	Cost value	P Losses	Cost value	P Losses
BC(0%, 0%)	802. 7967	9.5672	802. 7967	9.5672
C1(5%,5%)	716.6444	8.2116	716.4902	8.2116
C2(5%,10%)	676.4108	7.6807	675.1642	7.7363
C3(5%,15%)	636.8641	7.0061	636.8572	7.4735
C4(10%,10%)	636.2296	7.0481	637.1197	7.0481
C5(10%,15%)	598.9328	6.7223	598.6102	6.7223
C6(5%,20%)	601.0504	6.5257	598.5816	7.2212
C7(5%,25%)	567.0212	6.5833	563.0264	7.8526
C8(10%,20%)	564.8451	6.3288	562.0310	6.9317
C9(15%,15%)	563.5201	6.1619	563.5169	6.1619
C10 (5%,30%)	534.9251	6.4923	527.5405	8.7119
C11(10%,25%)	532.6877	6.2309	527.0159	6.6672
C12(15%,20%)	530.6857	6.0753	528.9801	8.2116

7. CONCLUSION

This paper proposes the application of DE method to the optimal power flow for a system that incorporates thermal units and wind farms during normal operation. The modified IEEE 30 system with six thermal generating units and two wind farms is used to analyze the effect of connected wind farm on the total generation cost, the voltage profile and to active losses. Based on the technical results it has been concluded that an optimal integration, location and utilization of wind farms give significant benefit example like such as reduction in the real power loss, fuel cost and amelioration in the voltage profile. The results obtained from different scenarios give a signal to the utility on what penetration level and location is optimal with respect to active power losses and voltage profile, when confronted with sites having similar wind regimes.

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Dr. Linda SLIMANI
Prof. Tarek BOUKTIR

Dep. of Electrical Engineering
University of Sétif, Sétif, Algeria
E-mail: Slimani_b_linda@yahoo.fr,
tarek.bouktir@esrgroups.org

Dr. Linda SLIMANI received the B.S degree in Electrical engineering from Setif University (Algeria) in 1990, his MSc degree from Setif University (Algeria) in 2005 and PhD degree in power system in 2009. His area of interest is the application of the metaheuristique methods in Power systems Analysis. Currently she serves as associate professor at the Department of Electrical Engineering in Ferhat Abbes University (Setif), ALGERIA.

Prof. Tarek Bouktir was born in Ras El-Oued, Algeria in 1971. He received the B.S degree in Electrical Engineering Power system from Setif University (Algeria) in 1994, his MSc degree from Annaba University in 1998, his PhD degree in power system from Batna University (Algeria) in 2004. His areas of interest are the application of the métaheuristique methods in optimal power flow, FACTS control and improvement in electric power systems, Multi-Objective Optimization for power systems, and Voltage Stability and Security Analysis. He is the Editor-In-Chief of Journal of Electrical Systems (Algeria), He currently serves on the editorial boards of TELKOMNIKA Journal, Indonesia. He serves as reviewer with the Journals: Journal IEEE Transactions on SYSTEMS, MAN, AND CYBERNETICS, IEEE Transactions on Power Systems (USA), ETEP - European Transactions on Electrical Power Engineering. He is with the Department of Electrical Engineering in Ferhat Abbes University (Setif), ALGERIA. He is also the head of the research team "Algerian Smart Grid".