Optimal Number of DFIG Wind Turbines in Farm Using Pareto Genetic Algorithm to Minimize Cost and Turbines fault effect

A.Khattara[1], M. Becherif[2],M. Y. Ayad[3], M. Bahri[1] and A. Aboubou[1]
[1]Laboratory of Energy Systems Modeling, UMKB University Biskra, Algeria
[2]FCLAB FR CNRS 3539, FEMTO-ST UMR CNRS 6174,
University of Technology of Belfort-Montbéliard,90010 Belfort Cedex, France
[3]Industrial Hybrid Vehicle Applications, France
a.khattara@mselab.org, mohamed.becherif@utbm.fr, ayadmy@gmail.com, m.bahri@mselab.org, a.aboubou@mselab.org

***Abstract*—With the development of power system, the wind power is considered as a promising solution due to its properties (clean and free source energy, high efficiency). Doubly fed induction generator (DFIG) wind turbines are widely used today in wind farms and their installation and maintenance raise many technical problems such as the minimization of the wind turbine fault effect on the grid and cost minimization.In this paper, a mathematical approximation and a Pareto genetic algorithm program aredeveloped to calculate the minimum installation and maintenance cost of a wind farm with the minimum lost of power during permanent and transient line fault. This approach allows obtaining the optimal number of DFIG wind turbines that should be connected in the same bus regarding the considered criteria. A typical IEEE 14-bus network is modeled using the PSAT to verify the line fault ride through (LFRT) capability of the farm to evaluate the cost effectiveness and the fault effect.**

Keywords—Distribution; DFIG; Line fault;Pareto;Genetic algorithm; PSAT;LFRT.

I. INTRODUCTION

As a fast growing energy source, wind power is of proved technique, high reliability, low cost, scale-economic and environmental friendly. In the meaning time, there are many issues related to the large-scale integration of wind power into electric network waiting to be investigated. The integration of wind energy into distribution networks gains special interests today, where several studies propose different solutions to this integration.

To evaluate maximum wind energy exploitation in active distribution networks, a method based on a multi-period optimal power flow analysis is proposed by P. Siano [1]; D. Jayaweera in [2] proposed a novel methodology for the customer security assessment with high penetration of wind power in modern distribution networks.The validity of the proposed method in [3] is examined by applying it on a standard radial 9-bus distribution network and a realistic 574-bus distribution network. The paperin [4] evaluates the effectiveness of different commercial relay functions in a local passive anti-islanding process for a permanent-magnet synchronous generator (PMSG)-based wind farm which is interfaced with a radial distribution network.

The integration of wind power to power systems; especially a weak distribution networks is one of the main concerns of the power system engineers. Voltage control and reactive power compensation in a weak distribution networks for integration of wind power represent main concern of [5]. The problemcited in [6] is viewed from MATLAB/Simulink simulation of weak distribution network and wind power integration in this network. Without reactive power compensation, the integration of wind power in a network causes voltage collapse in the system and under-voltage tripping of wind power generators. For dynamic reactive power compensation, when, STATCOM (Static Synchronous Compensator) is used at a point of interconnection of wind farm and thenetwork; the system absorbs the generated wind reactive power while maintaining its voltage level.Genetic algorithm, and the way of "breaking circle", is employed to seek optimal network reconfiguration scheme with wind turbine under mono-scenario and the multi-scenario. The experimental results from a 33-bus distribution network with wind turbine have shown the efficacy and feasibility of the novel approach [7]. It is demonstrated in [8] that to avoid the disconnection of DFIG wind turbine from the network during the line fault ride through,the wind turbine should be connectedto the distribution network.

Other researches study the cost problem when integrating the wind turbines to the power system; the objective of [9] is to measure the impact of grid location of wind farms on economic and operational parameters of a power system in the lifetime of a wind farm project. The optimization of the generator to rotor (turbine) ratio (GRR) is focused with respect to the cost of energy (COE). Using a wind speed, a power generation, and a cost model [10]. A methodology used to design a small wind turbine of low cost for domestic use is presented in[11].The influence of a wind generator in the optimization of the economic dispatch problem is also studied in [12].

In the past, the wind turbines were disconnected from the grid during the line fault, but according to the new codes of networks, researchers propose several ideas in those last years to remain the wind turbine connected to the grid during the line fault contributing in the stabilization of the network. In [13], a hybrid control scheme for energy storage systems (ESS) and braking choppers for fault ride-through capability and a suppression of the output power fluctuation is proposed for permanent-magnet synchronous generator (PMSG) wind turbine systems. A methodology based on Z-bus algorithm is proposed in [14] to determine the tripping status of wind farms for a worst case fault, so that it can be used in contingency evaluation procedure. It is demonstrated in [15] that the integration of DFIG wind turbine to the transmission network risks to disconnect this wind turbine from the network during the line fault.To avoid the disconnection problem from the grids, the DFIG wind turbine should be connected to the distribution network.

When the wind farm is disconnected from the network during the line fault, the power supposed to be injected to the grid from this farm is lost.To minimize the power loss during the line fault, one should dispatch the wind turbines to different buses, but the cost to install each wind turbine alone in a bus is huge. In this paper, a multi objective function is developed using Pareto genetic algorithm to determine the optimal number of wind turbine in farm with minimum installation and maintenance cost and minimum power loss during the line fault; the obtained results are validated via PSAT when simulating the fault.

II. OPTIMIZATION PROBLEM

A. Cost and power loss equations

Consider C_w in Euros as the total cost to install one wind turbine

$$C_w = C_e + \alpha . P_w \tag{1}$$

Where C_e (Euros) is the cost of investment of one wind turbine, P_w is the power generated by the wind turbine and α is the factor of maintenance; this factor represents the maintenance cost of 1 MW generated power from a farm in one year.

To install more than one wind turbine in the same bus (farm) the cost will be reduced in factor of installation β, where β represents the reduction in cost when more than one wind turbine will be installed together in one farm, and it is given by the manufacturer.

Below the considered case:

The cost to install one DFIG wind turbine of 5MW in one station is 5 million Euros [27]. While installing a farm of 14 wind turbines the total cost reduces by a factor β. This reduction (economy) is made when different wind turbines are joined in the same bus. Authors suppose this reduction to be of 0.6 as a case of study.

If 14 wind turbines are installed separately in different buses, the total cost will be of 71.05 million Euros, and if they are installed together in the same bus the total cost will be of 42.64 million Euros. The cost reduction is obtained using the factor β, where β depends on the number of wind turbines installed together in one bus, if N_w=1 so β=1 and if N_w=14 then β=0.6, β is given by (2). The β reduction is chosen to be logarithmic to avoid the linear reduction and the case of zero.

$$\beta = \frac{1,72}{1,72 + Log(N_w)} \tag{2}$$

Where

$$0 \leq \beta \leq 1 \tag{3}$$

Where N_w is the number of wind turbine to be installed.

The cost (C) to install a farm of N_w wind turbines is

$$C = \beta(N_w . C_w + \alpha \sum P_w) \tag{4}$$

To avoid the disconnection of large amounts of power generated by a farm in the case of permanent or transient line fault, it is advised to dispatch the wind turbines installed in this farm into different buses (ideally one turbine in each bus if considering only the lost power minimization).

$$P_{loss} = P_w . N_w \tag{5}$$

Where P_{loss} is the power loss in the case of permanent or transient line fault. If different wind turbine (N_w) are connected to the same bus, money is saved by joining them, but a large amount of power is lost when having the LFTR. In the other hand, putting one wind turbine in each bus reduces the lost power in the case of LFRT but it maximizes the installation and maintenance cost.

B. Genetic Algorithm

Genetic algorithms (GA) are a subclass of evolutionary algorithms where the elements of the search space G are binary strings (G = B∗) or arrays of other elementary types.

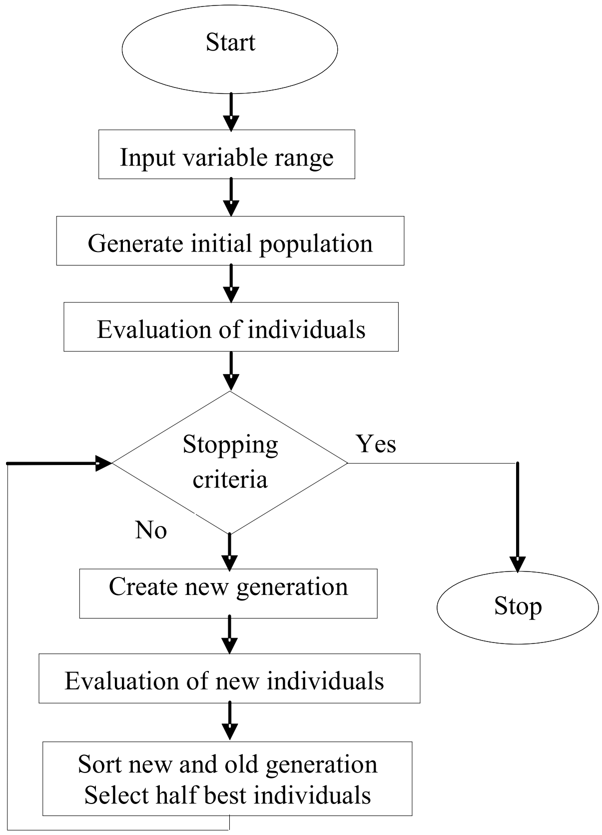

Fig. 1. The basic cycle of genetic algorithms.

As sketched in figure 1, the genotypes are used in the reproduction operations whereas the values of the objective functions f ∈ F are computed on basis of the phenotypes in the problem space X which are obtained via the genotype-phenotype mapping [16], [17], [18], [19] and [20].

C. Pareto Optimization

The mathematical foundations for multi-objective optimization which considers conflicting criteria in a fair way has been laid by Vilfredo Pareto 114 years ago [21, 22]. Pareto optimality became an important notion in economics, game theory, engineering, and social sciences [23], [24], [25] and [26].

An element x⋆∈ X is Pareto optimal (and hence, part of the optimal set X⋆) if it is not dominated by any other element in the problem space X. In terms of Pareto optimization, X⋆is called the Pareto set or the Pareto Frontier.

III. Simulation Results

Fourteen DFIG wind turbines of 5 MW are chosen to be installed in a typical network IEEE 14 bus; the cost to install one wind turbine is 5 million euros. When the installation of 14 wind turbines is dispatched in different buses, the power loss during permanent or transient line fault is small. In the other hand, the installation cost will be expensive 14*5 million Euros. If those wind turbines are installed in the same bus, the cost is reduced, but the power loss in the case of line fault will be large. Between those constraints, an optimal number of DFIG wind turbines in a farm should be found to have a good line fault ride through capability and minimum power loss during line faults with a minimum installation and maintenance cost.

Before using the Pareto genetic algorithm program, and for a comparison purpose, a mathematical approximation was formulated to find the optimal number of wind turbine that should be installed in a farm to minimize the power loss during the permanent and transient line fault and minimize the cost.

According to (4) and (5), the installation cost as function of the power loss is given by:

$$C = \beta(P_{loss} + \alpha P_{loss}) \qquad (6)$$

The table 1 gives the cost of installation (formula 4) and the power loss during line fault in all cases of number of wind turbine installed in each bus. Where the sum of wind turbines installed in each case is 14 DFIG wind turbines.

TABLE I. Installation and maintenance Cost And Power Loss During Line Fault In All Cases Of Number Of Wind Turbine Connected In The Same Bus

N_w	β	P_{loss} (MW)	C(million euros)
1	1,00	5,00	71,05
2	0,85	10,00	60,47
3	0,78	15,00	55,62
4	0,74	20,00	52,63
5	0,71	25,00	50,52
6	0,69	30,00	48,92
7	0,67	35,00	47,64
8	0,66	40,00	46,59
9	0,64	45,00	45,70
10	0,63	50,00	44,93
11	0,62	55,00	44,26
12	0,61	60,00	43,66
13	0,61	65,00	43,12
14	0,60	70,00	42,64

It is shown in table 1 that whenever the number of wind turbine installed in each bus (N_w) increases, the installation cost (C) decreases, but the power loss in the case of line fault in one bus (P_{loss}) increases as well.

The curve in Fig. 2 and the tangent of the curve are traced to obtain the optimal value between the installation cost and the power loss. Fig. 2 gives the cost as function of the power loss in the case of line fault; it is noted that when the P_{loss} is small the cost is large, and each time the (P_{loss}) increases the cost (C) decreases.

The optimal value obtained graphically in Fig. 2 is 13 MW of power loss corresponding to the installation cost of 57 million Euros. According to the table 1, those values are near to the case of 3 wind turbines in each farm, where the total installation cost is 55.62 million Euros and the power loss during the permanent or transient line fault is 15 MW.

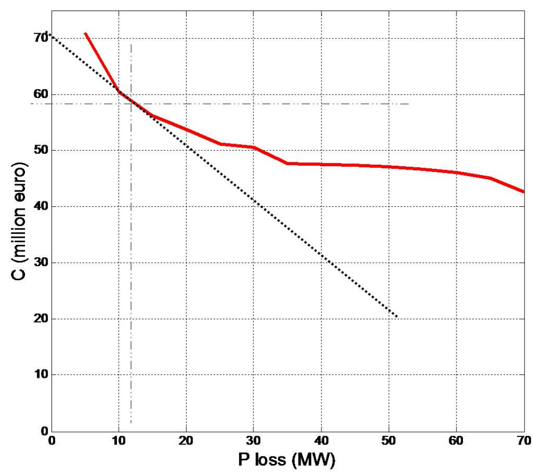

Fig. 2. Mathematical approximation

As mentioned above, a Pareto genetic algorithm is developed in this work to calculate the optimal value between the installation cost and the power loss during permanent and transient line fault.

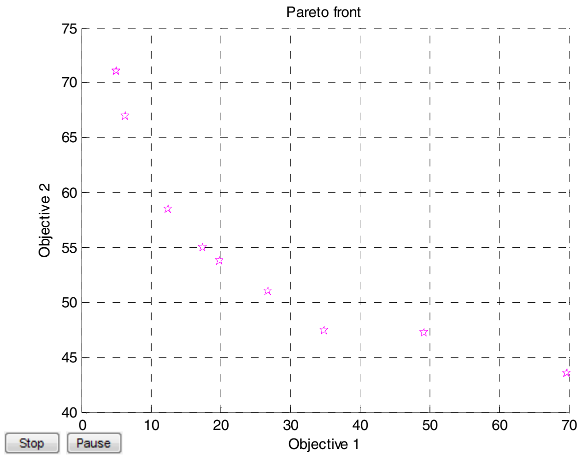

Fig. 3. Pareto genetic algorithm solution

This solution is found with the following parameters: Generation = 200, population size = 90, crossover = 0,75 and mutation = 0,03.

Optimal values of power loss and installation cost obtained by Pareto genetic algorithm are respectively 17,4554 MW and 55,0089 million Euros, and those results are corresponding to the wind turbines number grouped in three in the same bus in a farm.

The line fault ride through capabilities in extremity and optimal cases are shown using the model of IEEE 14-bus network in PSAT. A line fault is applied in the distribution part of the network in those different cases and the voltages are presented.

The line fault considered in this application is the worst case where the time fault is 500 ms, the line fault resistant is 0 Ω and the three phases are grounded. And it is considered that the weather and geographical constraints in all bus are done and are the same.

Firstly, each DFIG wind turbine is installed alone in a bus, and the line fault is applied.The voltage in the bus, where the line fault is applied before, during and after the line fault is presented in Fig. 4.

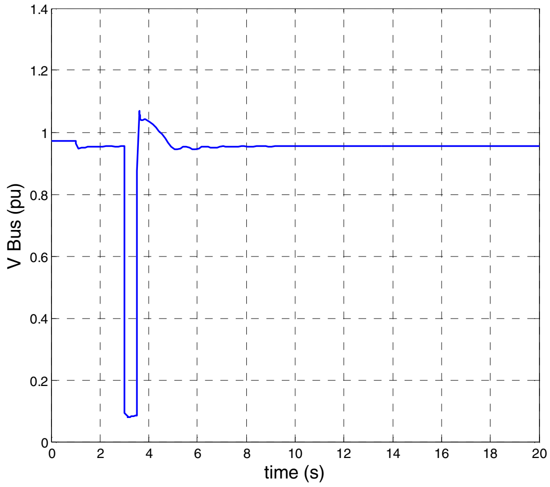

Fig. 4. Voltage in the case of each DFIG wind turbine alone in a bus before during and after the line fault

It can be easily observed in Fig. 4 that the voltage before the line fault in standard, and a voltage dip appears during the line fault, while the voltage returns to its standard value after the line fault; so the DFIG wind turbines have a good line-fault ride-through capability when they are connected separately to the network (minimum power loss).

In the second case the DFIG wind turbines are connected together as a farm in the same bus, the same line fault is applied. The voltage in the bus where the line fault is applied before, during and after the line fault is presented in Fig. 5.

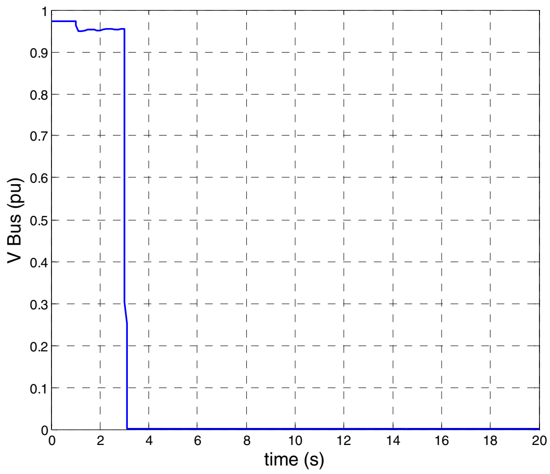

Fig. 5. Voltage in the case where all DFIG wind turbines are connected to the same bus as a farm before during and after the line fault

Fig. 5 shows that the voltage before the line fault is in standard, but during the line fault a voltage dip appears and it remains even though the line fault disappears. Consequently, the DFIG wind turbines indicate that they have a weak line-fault ride-through capability when they are connected together to the same bus.

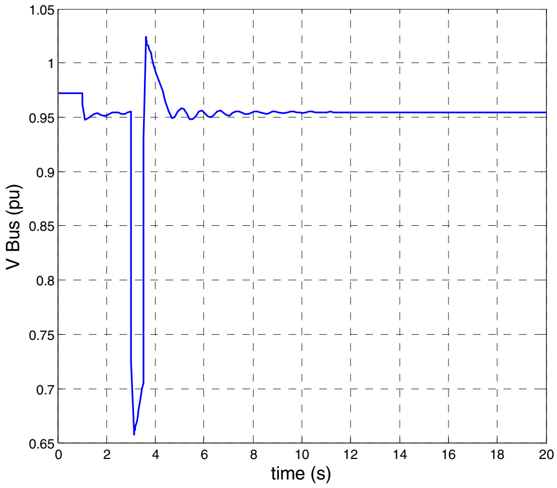

Fig. 6. Volage in different buses before, durig and after the line fault

The optimum DFIG wind turbines number found using the mathematical approximation is confirmed by the Pareto genetic algorithm and is equal to 3. The two DFIG wind turbines remained are connected together to a bus and the LFRT studied is on the buses where three DFIG wind turbines are connected. To validate the line fault ride through capability of a farm of 3 DFIG wind turbines connected to the distribution part of IEEE 14-bus network, different farm of 3 DFIG wind turbines are connected to different bus of distribution network part and a line fault is considered in the network. Then, the voltage where the line fault applied before during and after the line fault is given in Fig. 6.

The Fig.6 shows that the voltage before the line fault is in standard, then a voltage dip appears during the line fault, but it disappears after the line fault; so the farm of three DFIG wind turbines has a line-fault ride-through capability when it is connected to the distribution network.

A comparison between three cases of DFIG wind turbines installation is presented in Table II.

TABLE II. COMPARISON BETWEEN THE PROPOSED SOLUTIONS.

installation case	C (million euros)	P loss (MW)	LFRT capability
14 DFIG wind turbines separately	71,05	5,00	good
14 DFIG wind turbines together	42,64	70,00	weak
14 DFIG wind turbines groupedinto farms of 3	55,62	15,00	good

The good solution to avoid the loss of a large power during line fault is the installation of each wind turbine alone in a bus, but this solution is not typical and it is expensive when implemented. If the cheap solution is sought, all DFIG wind turbines should be installed in the same bus, but this solution may cause the loss of large power during the line fault and it has a weak LFRT capability. However, when those 14 DFIG wind turbines are separated to different farm of three, the cost of installation is not very expensive and the power loss is acceptable. In addition, it has a good LFRT capability.

IV. CONCLUSION

The integration of DFIG wind turbines to the networks opens several aspects of research. In this paper, the optimal number of DFIG wind turbines that should be installed in a farm according to the installation cost and power loss during permanent or transient line fault is investigated. The optimal value was given by a mathematical optimization, and then it was confirmed by the Pareto genetic algorithm.

It is demonstrated that the optimal number of wind turbines to be installed is three DFIG wind turbines in the same bus and shown that when assembled as explained, these farms have a good line fault ride through capability. The line fault ride through capability in this case was checked using the PSAT, where different farm of three wind turbines was connected to different distribution bus of IEEE 14-bus network. This paper uses two different optimization methods, mathematical approximation and Pareto Genetic algorithm, allowing determining the optimal solution for DFIG turbines assembling and connecting to avoid a large power loss during permanent or transient line fault at a reasonable installation and maintenance price.

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