Probabilistic study of the maximum penetration rate of renewable energy in an island network

H. Bayem, L. Capely, F. Dufourd, M. Petit

***Abstract*—This paper addresses the determination of the maximum penetration rate of renewable energy sources (RES) in island power systems. This issue is analyzed through a probabilistic approach which gives an interesting set of results giving to system operators the possibility to faces challenges brought up by massive RES connections. RES, especially wind farms and photovoltaic solar plants may affect significantly power systems in terms of power flows (risk of congestions), voltage level, stability or reserves. For the purpose of this study, a probabilistic model of the power system has been developed. The mathematical model mixes the probabilistic characterization of the power system with a probabilistic RES production model to estimate defined reliability criteria. Practical application on a typical French island network is presented and contributions of the probabilistic methods are discussed, compared to the deterministic approach. The maximum penetration rate obtained with the last one is 13% instead of 30% with the probabilistic approach. The large quantity of results obtained with the probabilistic approach allows further analysis such as the influence of RES on the dispatching and the impact of the sudden RES generation loss.**

***Index Terms*— penetration rate, probabilistic method, island network, renewable energy sources, wind generation, photovoltaic generation**

I. Introduction

THE necessity to combat climate change and pursue sustainable development has leaded European union (EU) energy policy makers to be strongly engaged in fostering the development of renewable energy sources (RES), particularly in the electricity sector. The first step of the fulfillment of this commitment is the “white paper” on renewable sources of energy issued in 1997 [1], where a target for the EU was set consisting of an indicative objective of 12% for the contribution of RES to the EU’s energy demand by 2010. Later, many documents where issued by the European commission (e.g. the directive 2001/77/EC [2], where the target was set at 22.1% of RES share on EU energy consumption by the year 2010, the “green paper” on the European strategy for sustainable, competitive and secure energy [3] issued in March 2006). Finally the Council of EU, held in March 2007 [4], have undertaken firm commitments for the new energy policy; among the conclusions was a target of 20% RES share in the energy consumption by the year 2020.

All those policy decisions, accompanied with incentive measures taken by each European state, has leaded in an increasing development of RES in the power system, particularly in France during the last five years. As the consequence, the integration of RES into the French power systems is becoming a hot issue. Various aspects have to be considered, such as power quality, steady-state and short-circuit currents, possible network congestions, fault-ride-through capability, power system dynamics and stability, etc. Integration issues are more significant in island networks because of their relative weakness [5],[6] (no interconnections, small number of generation units …).

In a power system, many variables are better characterised using probabilistic description. Loads are usually well described with a Gaussian probability law [7] production availability with binomial laws [8]. Wind and solar power production depend on wind speed and solar irradiance, which are of stochastic nature [9],[10] . Therefore, the probabilistic characterisation of wind and photovoltaic power using probability density laws fit better with their real behaviour [9],[10].

Considering the probabilistic nature of the wind/photovoltaic power combined with the one of loads and other contingencies (production unavailability), a probabilistic approach may therefore be preferable to study the maximum penetration rate of wind and solar power in power systems instead of using a deterministic approach. Moreover, the main drawback of a deterministic study is that it analyses predefined extreme situations which may not be the ones leading to limits violations [9].

This paper presents a new methodology to calculate the maximum penetration rate of renewable energy in an island power system and presents results of a study case. The study is divided in two sub studies, the first concerning the limitation of RES due to minimum reserves requirement of the system and the second which deals with networks related (congestions, voltage stability..) limitations of RES penetration rate. First the general methodology of a probabilistic study and the specific aspects of each sub study will be presented, then the results will be discussed.

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II. Methodology

A. General principle

The general principle illustrated by the Figure 1 consists in characterizing power system parameters by probability laws. This approach is justified as the main parameters impacting the system performances (unavailability of generators, lines, demand and RES generation) are of stochastic nature. A large number of system configurations, covering the scope of all possible values of wind and photovoltaic production, conventional production and loads, is created according to probability laws and with respect of correlations. These configurations are simulated and results are analyzed.

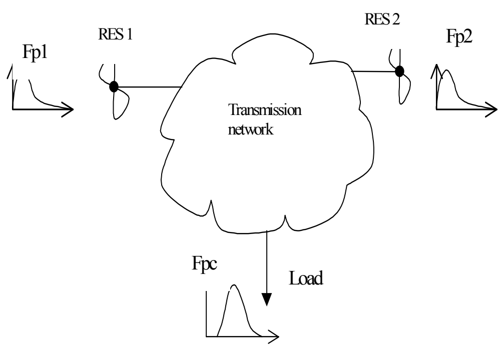

Figure 1: Illustration of the general principle

B. Steps

The methodology consists of five steps:

1) Criterion definition

A reliability criterion has to be defined. This criterion represents the admissible risk. For instance the operator can decide to have only 1% of simulated configurations which are not adequate i.e. 1% of the simulated configurations can lead to a limit violation. The criteria will define a boundary between acceptable and unacceptable situations.

2) Uncertainties characterization

All the uncertainties of the electrical system (loads, availability of generators and lines) are characterised with probabilistic laws. Gaussian laws are used for loads [7] and binomial laws are used for conventional generation units' availability [8].

3) RES production Characterization

Wind farms and solar plants are placed on the network according to the wind/solar resources of sites and to the penetration rate to be tested. Chronological hourly measurement of wind speed or horizontal irradiance is analyzed for the sites. The probability density functions of the power produced by each wind farm and PV solar plant is derived from the ones of the wind speed and irradiance of the sites, convolved with the electric models of the wind turbines and solar panels. Figures 2 and 3 show the probability density functions describing wind and PV productions in different sites as well as total production of the island. For our study case, the overall wind production reaches its extreme values (zero and maximum load factor) less frequently than each site production (smoothing effect). There is almost no smoothing effect denoted for PV production due to the high correlation between the irradiance of each site.

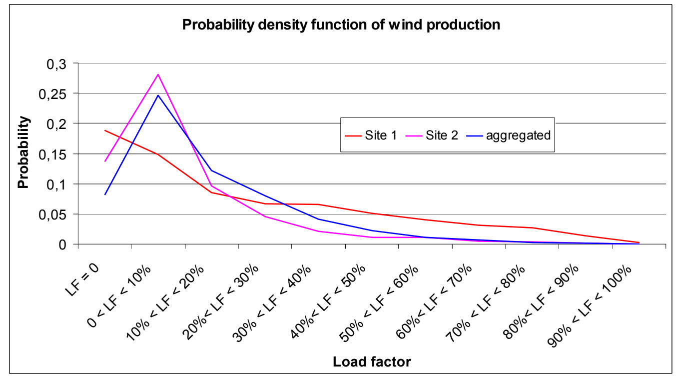

Figure 2: Example of probability laws for wind production

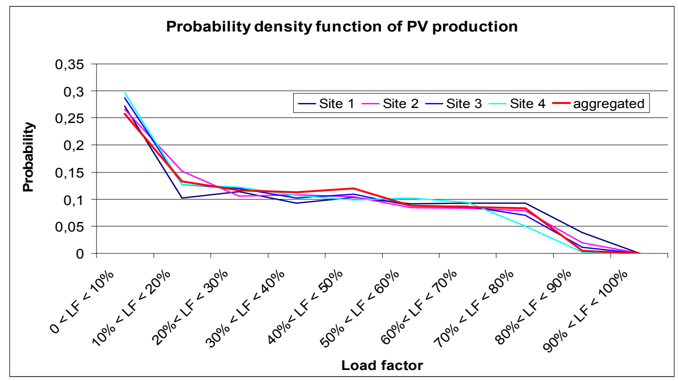

Figure 3: Example of probability laws for PV production

4) Simulations

With results of the previous steps as input, many network situations are generated using monte-carlo sampling techniques based on the probability laws. Therefore, a large number of system configurations, covering the scope of all possible values of wind and solar production, conventional production and loads, is created. Then, those configurations are assessed in terms of adequacy of generation and reserve for the *reserves adequacy study* and of power flows, voltage limits for the *static network study* and are classified as acceptable or unacceptable according to constraints.

5) Results analysis

Results are statistically analysed and compared to the reliability criterion chosen. The objective is to find at which level of wind and solar power penetration problems occur leading to a violation of the reliability criterion.

III. Study Case

The methodology was applied to calculate the maximum RES penetration rate of test system which represents a typical French island network including more than 15 conventional thermal units, hydro plants and a high voltage transmission grid. Wind power is simulated in two sites, PV power in four sites.

In this study, the penetration rate is defined as the installed RES capacity divided by the peak load of the system.

IV. Reserves Adequacy Study

In French Island power systems, the first limitation of the maximum penetration rate of RES comes from additional operating constraints. The main constraint is the minimum reserve requirement. This reserve is supplied only by conventional thermal units which are not operated below a certain threshold of their rated power [6].

Let us consider that the minimum reserve requirement *R* is supplied by *n* thermal units with "technical minimum" P_{mi} (*minimum loading level of unit i*), then to meet the reserve requirement, the n units will generate a minimal thermal power

$$P_{th\_m} = P_{m1} + P_{m2} + ... + P_{mn} \quad (1)$$

Since this power should be absorbed by the demand, the penetration rate of RES is limited by the following constraint:

$$Load(t) - P_{res}(t) \geqslant P_{th\_m} \quad (2)$$

Where:

- *Load(t)* is the demand at moment t
- P_{res} is the RES output at moment t

A. Deterministic approach

This approach consists in verifying equation (2) in the most restricting case so that to be sure it is verified in all the situations. This case corresponds to system minimal load and maximum RES output.

With this approach the penetration rate ($P_{res}/Load_{max}$) obtained is **13.3%**.

B. Probabilistic approach

The probabilistic method is already described in paragraph II; next more details will be given on steps 1, 4 and 5.

1) Criterion definition

The transmission system operator (TSO) must operate the system within the normal conditions of reliability, stability and security. With the increasing development of RES, TSOs have to be able to operate the transmission system with same performances while maintaining RES generation units connected almost all the time. Given that, the criterion retained for this study is "less than 0.1% of RES units' disconnection due to reserves inadequacy". That means:

$$\Pr obability\left[Load(t) - P_{res}(t) < P_{th\_m}\right] < 0{,}1\% \quad (3)$$

Since reserve inadequacy situations correspond to period when there is not enough thermal (flexible) production on the system to ensure the reserve minimum requirement, the common sense solution is to cut part of the RES production. Given that, (3) can be translated like "RES production shouldn't be cut more than 0.1% of the time" corresponding to roughly 9 hours per year which is quite reasonable for farm owners.

2) Simulations

Simulations consist in:

- Generating time series of system demand and RES output according to probability law of those variables;
- Comparing the result time series of $Load - P_{res}$ to the minimal thermal power P_{th_m} and then calculating the probability to have: $(Load - P_{res}) < P_{th\_m}$
- Increasing the RES power until the criterion 0.1% is reached.

3) Results

Figure 4 shows the variation of the probability to have: $(Load - P_{res}) < P_{th\_m}$ with the RES penetration rate. With the defined probability laws, the reserve requirement and a risk threshold of 0.1%, the probabilistic approach lead to a maximum RES penetration rate of 30%.

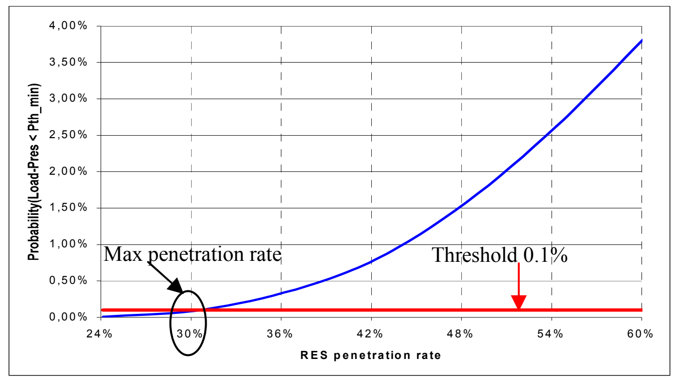

Figure 4: Variation of probability $\{(Load - P_{res}) < P_{th\_m}\}$ with the penetration rate

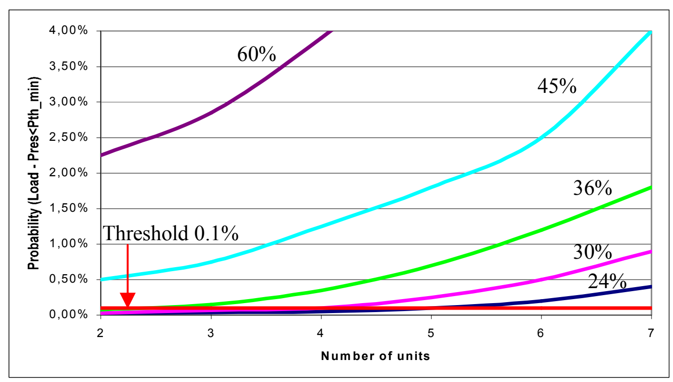

Figure 5: Impact of the number of units dedicated to reserve requirements

Figure 5 is the result of a sensitivity study of the penetration rate to the number of units dedicated to fulfill the reserve requirements. One can note that the penetration rate decreases as the number of units increases.

V. Static Network Study

A. The tool

This study is performed using a probabilistic software tool called ASSESS, developed by RTE (French TSO) and National Grid (English TSO). ASSESS allows the analysis of as many network situations as required to take into account the uncertainties with confidence.

ASSESS is dedicated to system planning and operation. ASSESS can use different electrical computational code: static or dynamic. The present study is done using the AC optimised power flow TROPIC-OPF which minimises, with respect to the AC thermal and voltage constraints, the economical cost of the system (merit-order start-up followed by the solving of the network constraints).

B. *Methodology*

1) *Definitions*

Fault: Congestion or voltage problem;
Fault variant: System configuration which leaded to a fault;
Fault rate: Number of fault variants divided by the total numbers of simulated variants.

2) *Criterion definition*

The probabilistic criterion was obtained by simulating, in a one year period, the reference system which is defined as the island power system without new RES added.
The annual fault rate obtained is **0.3%**. It means that 0.3% of simulated variants leaded in a fault. This will be the probabilistic reliability criterion for further studies.

C. *Results*

First as a general result we calculated the fault rate for different penetration (table 1). The maximum penetration rate obtained without violating the criterion is **30.2%.**

TABLE 1 VARIATION OF THE FAULT RATE WITH THE PENETRATION RATE

Penetration rate	4% (reference case)	30%	45%
Fault rate	0.3%	0.3%	0.4%

D. *Analyses*

1) *RES' impacts on the dispatching*

Further analyses made concerning the 30% RES penetration rate case brought to light impacts on the system generation dispatching. These impacts can be seen in table 2, figures 6 and 7 which present the share of each type of production in the total dispatching for the reference case and the 30% penetration rate case. A RES penetration rate of 30% allows the supply of 10% of the annual energy demand shifting the share of thermal generation from 80% to 73%.

TABLE 2 : SHARE OF PRODUCTION IN % (ANNUAL AVERAGE)

	RES	Diesel	Hydro
Penetration rate 4 %	2	80	19
Penetration rate 30 %	10	73	17

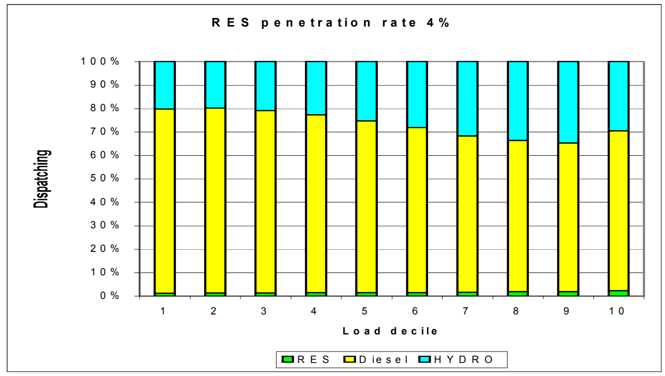

Figure 6: generation dispatching for the reference case

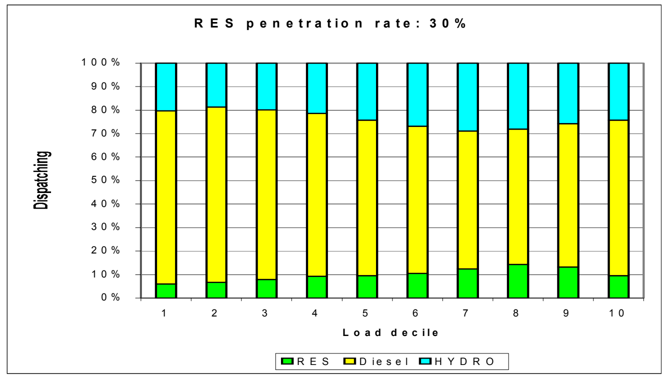

Figure 7: generation dispatching for 30% penetration rate case

2) *Impact of RES sudden loss*

In island systems where the transmission network is isolated the issue of a sudden loss of part or all RES generation must be taken into account. Figure 8 shows the ability of the studied system to cover by its reserves level the loss of a certain RES capacity. For a 50% sudden loss of RES generation, we have a 3.5% risk of not being able to cover the loss by the available reserve. This small risk combined with the fact that the probability of losing suddenly 50% of the RES generation is very small in our case makes the event *"system imbalance due 50% RES sudden loss"* very rare.

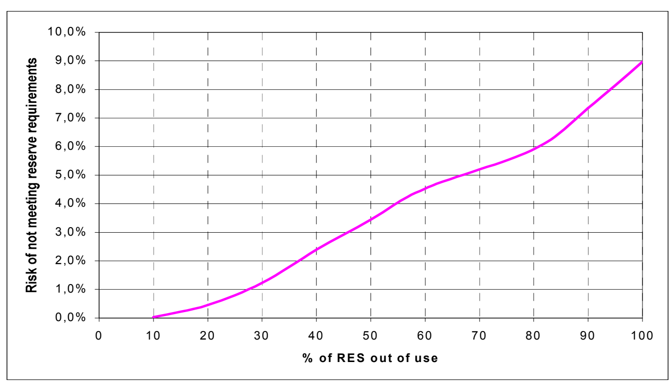

Figure 8: risk of system imbalance due to RES generation loss

VI. Conclusion

In this work a probabilistic approach for the determination of the maximum penetration rate of renewable energy sources (RES) in an island network was presented. The study was made regarding two aspects: reserves adequacy and static network constraints (congestion and voltage stability). With the RES location chosen and the probabilistic laws obtained as hypothesis, an important result is that the first limitation for RES penetration rate is the reserve adequacy. The reserves adequacy study leaded to a maximum penetration rate of 30%. The static network study didn't bring into light major limitation to the penetration rate.

The study made in this work demonstrated the contribution of the probabilistic approach in two aspects. The first is related to the general result which would have been 13% maximum penetration rate with the deterministic approach instead of 30%. The second concerns the large quantity of results obtained by the probabilistic approach. All those results permit further analysis such as the influence of RES on the dispatching, with in our case 7% of the thermal generation replaced by RES. An analysis of the impact of the sudden RES generation loss showed that a 50% RES loss results in 3.5% probability of system imbalance.

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