Limits of Repowering Renewable Sources in Electric Islands

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Abstract

The paper proposes a Methodology to evaluate the limits of Repowering or implantation of new Renewable Energy Sources units in an Isolated Electric System, that is an Electric Island. The Power generated by Renewable Sources is highly variable and unpredictable because it is related to the randomness of the weather, mainly wind. This variable generation introduces a high risk for the grid stability, more dangerous in electric islands that do not have the support of external systems. The Methodology is based on the Analysis of the Power Time series of the current Electric System and on the evaluation of a set of numerical constrains about the Power of non-Renewable Sources and their Gradients. Convex Set Theory and Linear Programming are used to decide if the numerical constraints are feasible or unfeasible, which implies Service Faults on the Electric in a future Repowered State. The Methodology is applied to the Electric System of Gran Canaria Island, a small scale system of about 500MW daily demand peak.

The results suggest that the critical factor in the power regulation in an increasing renewable energy sources is the lack of adaptation of steam and combined cycles plants. The fail events happen at night with low demand and with high peaks of wind. The lack of elastic adaptability can be in practice solved by the TSO by reducing the power of wind generators, usually by programming skew orientation of rotors.This technical solution to preserve the grid stability implies a suboptimal use of the high cost infrastructures and a waste of the renewable energy sources.

Keywords: Renewable Energy Sources, Power Planning, Numerical Constrains, Convex Sets, Linear Optimization.

1 Introduction

Repowering of Renewable Energy Sources (RES) is a general trend[1][6] in advanced countries motivated by the social awareness to improve the Environment and to avoid the greenhouse gases emissions. The repowering applied in an Electrical System refers to the power increments of currently installed units as well as to the implantation of new ones. However, RES are random sources, only partially predictable, which introduce uncertainty in the Control of the Electric Systems, therefore the repowering of RES increases the uncertainty and the risk of Quality Fault.

Electric Islands are usually small Systems without the availability of external sources/sinks to support the Quality Control of the Service and the Grid Stability, therefore RES repowering in Electric Islands is a high risk activity, mainly if no public investments are carried out to increase the adaptability of the current Electric System. The introduction of Energy Storage Systems is a way to reduce the risk of RES repowering[5][3], but it requires additional public investments.

The aim of this paper is to present a Methodology to evaluate the limits of RES repowering in Electric Islands based on the analysis of its power time series. The results provided by such Methodology will increase the knowledge of Modern Electric Systems and also can be useful for the Planners and Public Authorities involved in the Technical and Financial decision about Electric Systems, mainly in small Islands and Archipelagoes.

Power Time series are data collections that do not contain all the information about an Electric System, but contain the information about how the System has been adapted to the demand changes as well to the randomness of the current implantation of RES. The proposed Methodology will use such dynamic information to evaluate the limits of the current System on its adaptation to a process of increasing RES power.For carrying out the analysis, two main resources will be analysed: the Power to support the demand and the Gradient to support the changes.

The Control of Public Electric Systems involves several levels[1], from the sort-time levels focused on Voltage and Frequency Control, middle levels focused on reserve management, to long-time levels focused on Power Planning. When a contingency happens, the lower levels involved in the Control of Voltage and Frequency run around in periods of time lower than 10 minutes[2]. Usually, RES generated events are slower, they fall in the scale of several minutes involving the use of spinning and non-spinning reserves. In Spanish Regulations, primary and secondary levels are the lower ones, and the tertiary level, involved in RES events, dispachs in the order of 15 minutes[4].

To estimate the limits of a current System in a simulated state of increased RES Power, we have adopted some hypothesis. The first hypothesis used in the paper is that the changes in the repowered Electric System are bigger in magnitude, but qualitatively similar to the registered in the time series of the original, previous to the repowering. An Electric Island is mainly a limited geographical area, such as the atmospheric randomness will be constant for all the older and newer Systems. Only a radical change in RES technology will invalidate this hypothesis of qualitative behaviour. The second hypothesis is that RES repowering will impact in the lower levels of the Control related to the *sub-ten minute events*, but it will mainly impact in the involved in the upper levels concerning reserves.

The methodology presents a case study for the Gran Canaria Electric Island. The Power Time series include renewable sources (wind and photovoltaic) as well as fossil sources (diesel, combined cycle, steam and gas turbines). Although combined cycle systems have both gas and steam turbines, the available data for the combined cycle is the joined value. The data for gas and steam turbines are the related to alone units do not included in combined cycles.

To analyse an Electric Systems, two approaches are possible. The first is an internal approach based on detailed data available or provided by the Transport and System Operator(TSO). The second is an external approach, based on the global activity of the Electric System.

Unfortunately, Red Electrica Española (REE), the Spanish TSO is highly reluctant to provide detailed data suitable for extensive computer analysis performed by independent researchers. The data used in this paper have been collected by hand from the web page of REE. Consequently, the used time series can not be large. The period covered in the analysis is October of 2015 in time-steps of 10 minutes. The length of the time series is $31 \times 24 \times 6 = 4464$. It includes programmed demand, predicted demand, real demand; also the split production in different sources: combined cycle, diesel, gas and steam turbines, photovoltaic and wind. The time series has some anomalies that have been corrected by interpolation.

Even to study a short period of time, the set of numerical constrains related to every one of the non-Renewable sources and their Gradients for each time-step can generate a high dimension problem. A Segmentation of the time series has been implemented to reduce the complexity of numerical algorithms, such as each individual segment is a subset that covers a period of time with null RES power in its bounds, the start and end. This Segmentation allows to evaluate the repowering for each segment independently.

The time series has some anomalies, the register for 10/26/2015 do not exits at 14:10 and the production data for 14:30 are null. Both are corrected by using linear interpolation from the neighbours data corresponding to 14:00, 14:20 and 14:30 respectively. The second data anomaly is that the real demand is different of the sum of the production. May be that the production be greater that the demand to take account the losses. However, in this case the difference between the demand an the sum of production is a random variable with null mean. That is, sometimes the production is greater than the demand, which is physically possible, sometimes the demand is greater than the production, that is impossible. We have concluded that the error source is that the data provided in the web page are rounded to one decimal digit, therefore the provided real demand rounded to such precision is different to the sum of the rounded production of each its components, because the rounded of the sum is different to the sum of the rounded data. We have solved this problem by approximating the real demand as the sum of the productions because the power losses in a small island must be also small.

The plan of this paper is as follows, Section 2 presents the Methodology, it includes the estimation of the operative limits, the definitions of the set of numerical constrains related to the power and Gradients of the fossil, non-Renewable sources. To solve the set of numerical constraint some mathematical concepts and tools of Convex Set Theory and Linear Programming[7] are used. Section 3 show the estimated repowering limits for the Gran Canaria Electric Island.

2 Methodology

The proposed Methodology is based on the following steps:

1. Obtain the Operative Limits for Power and Gradient of each of the fossil sources in the analysed period based on the actual Electric System activity.

2. Repowering the RES by introducing a multiplicative factor $\lambda \geq 1$, such as the renewable sources go from power $P_{rnw}(t)$ to $\lambda P_{rnw}(t)$, while fossil sources with current power values $P_i(t)$, will change to an unknown value $P'_i(t)$ in the Rrpowered System.

3. Construct the set of Numerical Constraints that define the valid values for the new Power distribution, $P'_i(t)$, and its Gradients.

4. Solve the Systems of Numerical Constraints to determine if the new distribution is feasible or unfeasible. The lower value of λ that generates an unfeasible state is the upper repowering multiplicative factor that allows the work of the Electric System into the Operative Limits. To solve the systems of Numerical Constraints for Power and Gradient we use Mathematical concepts and Computer tools from Convex Sets Theory and Linear Programming.

5. To solve the Numerical Constrains even in a limited time series, the number of constrains will be very high. We proposed a Segmentation of the whole time series in smaller periods called segments, such as every one of the generated segments has null RES power in its bounds, at start and at end of the segment. This allows to study large time series avoiding the curse of the big data volumes.

Table 1: Estimated Operative Limits of Power(MW) and Gradient(MW/m10^{-1}) in the studied period of Gran Canary Island

	ccycle	diesel	gas	steam	$\sum P_i$
P_{max}	364.44	44.40	56.16	219.36	684.36
P_{min}	99.28	0	0	42.96	142.24
ΔP^+	92.88	8.52	32.40	23.76	157.56
ΔP^-	86.40	41.52	21.72	38.40	188.04

2.1 Estimating Operative Limits

The Operative Limits of the Electric System can be obtained from the detailed knowledge of every one of the power units in the Systems. It must include also the knowledge about its operative cycles, repairs and maintenance. That level of so detailed information is not available because it is highly sensible data of TSO. A better approach is to obtain the current limits (that is extremal) in a period and correct such values with some coefficients. We have used a corrective factor of 1.2 for the upper limits and 0.8 for the lower ones.

$$\begin{aligned} P_{i(max)} &= 1.2 \max\left[P_i(t)\right] & (1)\\ P_{i(min)} &= 0.8 \min\left[P_i(t)\right] & (2) \end{aligned}$$

The positive and negative Gradients, ΔP_i^+ and ΔP_i^-, are estimations based on the data with positive and negative gradient, that is: $P_i(t+1) - P_i(t) > 0$ for the positive and $P_i(t+1) - P_i(t) < 0$ for the negative respectively:

$$\begin{aligned} \Delta P_i^+ &= 1.2 \max\left[(P_i(t+1) - P_i(t)) > 0\right] & (3)\\ -\Delta P_i^- &= 1.2 \min\left[(P_i(t+1) - P_i(t)) < 0\right] & (4) \end{aligned}$$

The units of the Power limits are MW, while the units for the Gradient limits are MW/m10^{-1} because we use the gradient refereed to 10 minutes time-step. Table 1 shows these limits for the Gran Canaria Island obtained in the October/2015 period.

2.2 Mathematical Model

In the current System, the demand $D(t)$ is supported by the renewable, $P_{rnw}(t) = P_{ph}(t) + P_{wnd}(t)$,and fossil sources $P_i(t)$ as:

$$D(t) = P_{rnw}(t) + \sum_i P_i(t) \qquad (5)$$

In a future state of unmodified demand, the repowering implies an increasing of RES, which must be prioritily dispatched in the System. Therefore the no-high priority sources, that is the fossil ones, must be re-planned from $P_i(t)$ in the current state, to the unknown $P_i'(t)$ in the repowered state. The repowering can be modelled as:

$$\sum_i P_i'(t) = D(t) - \lambda P_{rnw}(t) \qquad (6)$$

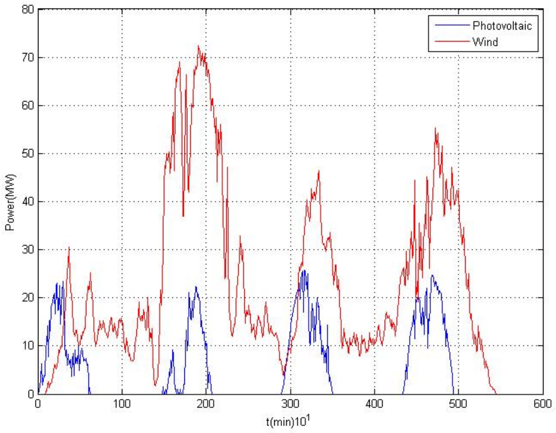

Figure 1: A segment with null renewable power at the bounds.

where $\lambda \geq 1$ is the relative implantation of photovoltaic and wind power relative to a the current status. The previous Equation is based on a global repowering of both RES. A study can be more general by analysing independently both photovoltaic and wind power impacts as: $D(t) - \mu P_{ph}(t) - \lambda P_{wnd}(t)$ in Equation (6).

Also, the unknown $P_i'(t)$ must verify the operative limits of the System:

$$P_{i(min)} \leq P_i'(t) \leq P_{i(max)} \qquad (7)$$

and also the Gradient limits:

$$-\Delta P_i^- \leq P_i'(t+1) - P_i'(t+1) \leq \Delta P_i^+ \qquad (8)$$

If N is the number of time-steps in the series, the number of unknown variables $P_i'(t)$ is $4N$, because i has the values of *ccycle*, *diesel*, *gas* and *steam*. The number of Numerical Constrains is N for Equation (6), $2 \times 4N$ for Equation (7) and $2 \times 4(N-1)$ for Equation (8). The total of numerical constraints, equations and inequations, is in the order of $17N$ and $4N$ the variable number. For the limited period studied $N = 4464$, the numerical problem is no-small, but for largest periods can require supercomputing facilities. The Segmentation of time series in smaller segments allows the decoupling of the large numerical set. Figure 1 shows a segment, a smaller series with null values of the RES at both bounds.

Segmentation is based on the following idea: if for a time-step t the RES power are null, so a solution for the repowered value at that time is the current value for all the fossil sources, that is $P_i'(t) = P_i(t)$. A segment of length $M \leq N$ is a decoupled subset of the whole series verifying: $P_{rnw}(1) = P_{rnw}(M) = 0$, therefore $P_i'(1) = P_i(1)$ and $P_i'(M) = P_i(M)$.

At the segment start is verified:

$$\begin{aligned} P_{i(min)} \leq & \quad P_i'(2) & \leq P_{i(max)} \qquad (9)\\ -\Delta P_i^- \leq & \quad P_i'(2) - P_i(1) & \leq \Delta P_i^+ \qquad (10) \end{aligned}$$

that can be simplified as:

$$\begin{aligned} P_i'(2) &\leq \min\left\{P_{i(max)}, P_i(1) + \Delta P_i^+\right\} & (11)\\ P_i'(2) &\geq \max\left\{P_{i(min)}, P_i(1) - \Delta P_i^-\right\} & (12) \end{aligned}$$

Similarly at the segment end, it must be verified:

$$\begin{aligned} P'_i(M-1) &\leq \min\left\{P_{i(max)}, P_i(M) - \Delta P_i^+\right\} \quad (13) \\ P'_i(M-1) &\geq \max\left\{P_{i(min)}, P_i(M) + \Delta P_i^-\right\} \quad (14) \end{aligned}$$

for $t = [3, M-2]$, must be:

$$P_{i(min)} \leq P'_i(t) \leq P_{i(max)} \tag{15}$$

$$-\Delta P_i^- \leq P'_i(t) - P'_i(t-1) \leq \Delta P_i^+ \tag{16}$$

2.3 Convex Set Theory and Computer Methods

Mathematical Model defined by the Equations (6), (7) and (8) comprises a large set of linear constraints that defines a convex region, that is a convex set of points, in a high dimensional space. This convex region is an infinite set of solutions for the constraint system. However, the constraints system can have no solution; in such case the convex set is empty. If the convex set has solution the constraints define a finite number of vertex points, which are constraints solutions, in the convex hull. Such vertex are the solutions for the maximization, or minimization, of linear goals as are used in Linear Programming(LP)[7].

A LP problem can have three different solution types: *unbound* if the convex region is open when the space variables are unbounded. But if the convex region is closed the two solutions types are *unfeasible* when the convex set is empty or *feasible* otherwise. In the unfeasible case the constraint system has not solution and it is not the matter what linear goal is used because the infeasibility of the LP problem depends on the constraints and does not depend of the goal.

In our proposal all the problem variables are bounded according the Equation (7), therefore the LP problem associated has only the feasible or unfeasible solutions. The test to detect the unfeasible case does not depend on the goal function of the LP problem, so it can be chose randomly.

The solution of the LP problem have been programmed in MATLAB by using the `linprog` function. It uses matrices for inequalities and equalities constraints, also upper and lower matrices for the variable bounds. The Equations (7), which are the related to power limits, have been used to define the lower and upper bounds, the gradient Equations (8) are coded as inequalities constrains, while the Equations (6) are coded as equalities constrains. The linear goal coefficients have random values, such as the program tests for the unfeasible solutions that does not depends of such random values because the unfeasibility depends on the constraints system.

The λ values are increased from $\lambda = 1$ until a value that generates an unfeasible solution. The process is performed in two steps. In the first, coarse increments $\Delta\lambda$ are used, such as the first steps stops when a feasible case is obtained for a λ value and an unfeasible case is obtained for $\lambda + \Delta\lambda$. In the second step a dichotomic search is performed to obtain a finer solution as the nearest (an error ϵ is allowed) unfeasible case to the limit between feasible and unfeasible cases.

Table 2: Estimated lower Power-fail $PF(MW)$ for segments in the studied period of Gran Canaria Island

Segment	Length(min)	$PF(MW)$
17	560	127.73
12	310	215.61
5	5570	240.81
18	590	261.44
4	1080	264.74

3 Results

The time series in the studied period has 23 segments larger that 4 hours. The shorter segments have low RES power and are avoided. More important that the λ value is the RES power of the segment. We define the Power Fail, PF, as the maximum power in a segment for the repowered RES where no solution can be found for the Equations (6), (7) and (8). This value PF is an estimation of a repowered that at least can generate one quality fault event.

$$PF = \max_t \lambda P_{rnw}(t) \tag{17}$$

The values of the Power Fail have been obtained for each one of the 23 segments. The lower values, that are the more relevant, are shown in Table 3. It shows that at 127.73 MW of RES, combining photovoltaic and wind, the system can not be regulated only by modifying the power of the non-RES sources by using the previously presented limits in Table 1.

Figure 2 shows the Demand and the RES power in the repowered case for segment 5. Figure 3 shows the no-RES power for this segment with the Power Fail obtained when the no-RES power reaches the lower minimum limit. In Figure 2 the Power Fail point is remarked; it happens in the lower peak of demand, at night, with a moderate peak of wind power. The no-RES sources can not be reduced below the P_{min} due to lack of flexibility of steam and combined cycles. In practice, this case can be solved if the TSO has control of the wind generators by programming a skew orientation of rotors.

Figures 4 and 5 show a similar case for the segment 17. In this case the Power Fail happens when no-RES power reaches P_{min}. The state of the Power Fail in segment 17 is very similar to the segment 5: low demand and a peak of wind power. However this last case happens at lower Power Fail.

In the studied time series covering a mouth of the activity of the Electric Island of Gran Canaria, we have verified that systems quality fails can be produced for repowering in the order of $\lambda = 3$. For analysis covering a larger time period is highly probable that fails can be found for lower repowering factor λ.

4 Conclusion

The Results have been obtained for a repowering of the combined photovoltaic and wind. However, in practice

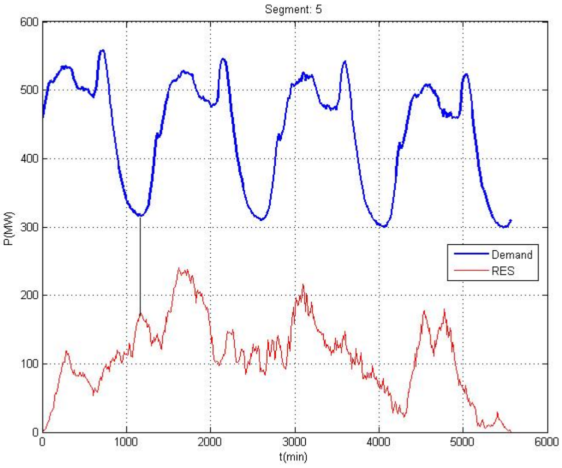

Figure 2: Comparative of the Demand and the Repowered RES in segmet 5. The fault event is remarked as the point with low demand, at night, and a moderate wind peak.

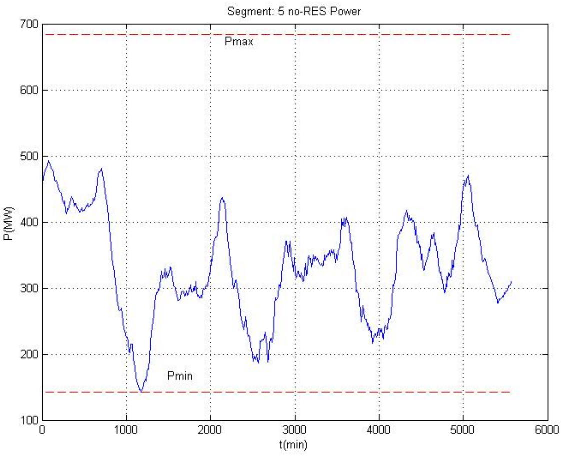

Figure 3: No-RES power in segmet 5 with Power Fail.

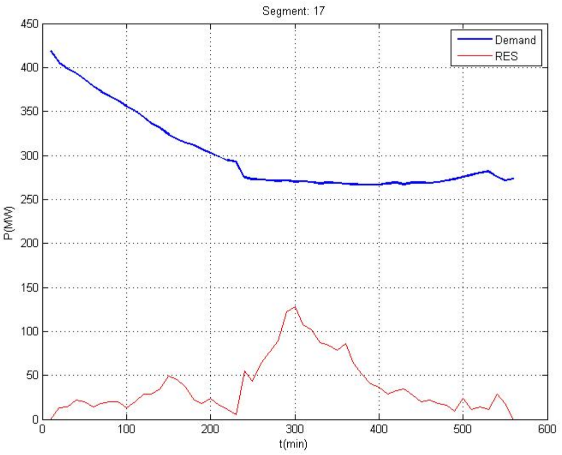

Figure 4: Comparative of the Demand and the Repowered RES in segmet 17. The wind power peak happens at very low demand.

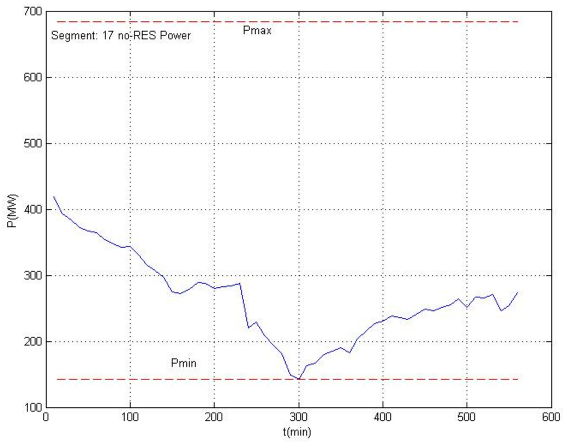

Figure 5: No-RES power in segmet 17 with Power Fail when P_{min} is reached.

photovoltaic sources are more time correlated to the demand because it is related to daily human activities. This means that photovoltaic sources have less probability to generate a Power Fail event in the case of reaching P_{min} as are mainly verifies in the studied time series of Gran Canaria Island. But wind sources are uncorrelated to human daily cycles, so they are the responsible of the undesired events.

The faults detected are a combination of three factor: low power demand at night, high wind power production and low flexible adaptation of steam and combined cycle plants in the lower power limits. Three solutions can be used to avoid the detected fault events. The first, the cheaper, is the suboptimal use of wind generator by using skew oriented rotors. The second, the expensive, the use of additional sinks as reversible hydraulic infrastructures to absorb the power excess in the low demand cases. The third, also expensive, the substitution of steam plants to more flexible diesel ones.

In general, photovoltaic sources are more expensive that wind ones, such as the massive introduction of RES is mainly in the wind technology due to these economical factors. A future study of the proposed methodology can be the repowering of only the wind part of RES. May be that a lower Power Fail can be found because the previously presented no correlation between wind and daily cycles. That is the right side of Equation (6) must be rewritten with constant photovoltaic and variable wind sources as:

$$D(t) - P_{ph}(t) - \lambda P_{wnd}(t) \tag{18}$$

Another critical event is the case of suddenly fall of RES, but this scenery is not presented in the time series of 10 minutes in the studied period. We hypothesize that this critical case can not be studied with the time step series of 10 minutes and that a smaller time step will be required to capture such critical events.

In a mix of photovoltaic and wind repowering upper the 100 MW, some events of grid instability can be highly frequent. Such events are mainly related to lack of flexibility of the steam and combined cycles plants. Such events can be technically solved by a suboptimal use of RES by using TSO controlled wind generators. Events of instability can be presented at lower RES power if the repowering is focused by the industry and government only in the wind technology. The Methodology presented in this paper can also be used to estimate the critical repowering.

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