Optimizing the Performance of Renewable Sources using Virtual Renewable Power Plants

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***Abstract* — The concept of "Virtual Renewable Power Plants - VRPP" enables several positive factors for the electric integration of Renewable Energy Sources (RES) and enables the optimization of its technical and economic performance by using the natural complementary of renewable resources availability. Moreover, the establishment of synergies between different RES contributes for the smoothing of time based fluctuation of the power delivered by the RES. The present work aims to identify the synergies between wind and photovoltaic (PV) plants, regarding their daily profiles complementarity and resource availability; as well as the technical and economic added value of a VRPP. Results show an increase of 5.3% in the capacity factor and 25% in the revenue when 2 MWp of PV are added to an 8 MW wind farm, and a potential benefit of 48% when adding a storage system of 2 MW (8 MWh), considering all infrastructural capacity limits. Moreover, the combined VRPP daily production profiles have a significantly higher correlation with the average daily load profile (0.82) than WTG (0.41) or PV (0.54) alone.**

Keywords- virtual power plant, power smoothing, RES power quality

I. Introduction

Power system managers and network planners face serious challenges to integrate renewable energy sources (RES) in large-scale. The fluctuation of power production in RES systems is one of the most important problems to be addressed. A wind farm and its connection infrastructure by itself are known to have a low capacity factor due to the natural variability of wind, the same occurring with a PV central.

The Virtual Renewable Power Plant – VRPP concept was developed to address the electric integration of several sources aiming to improve their capacity factor and better adapt the daily production profile to the load profile. The VRPP identifies the possible synergies and complementarities between different RES systems in order to make an effective use of these. The operation guideline of a VRPP is based on the establishment of a common control system to allow the creation of a merged daily production profile.

The present work addresses a realistic case-study of a combined wind and photovoltaic (PV) plant. We first describe and analyze the benefits of such a VRPP. Added value was obtained by increasing the capacity factor and improving the power quality while diminishing slow and fast fluctuations. Secondly the potential economic benefit is evaluated for (1) the hybrid wind/PV system and (2) the hybrid wind/PV plant with a battery energy storage system (BESS). The synergies identified may be of interest to both, the system's management and the developers, since often they represent a reduction in infrastructural needs and investments – i.e. interconnection transmission line, transformers and auxiliary equipment.

In the scope of the current work, time-domain models with the capacity to represent the detailed behavior of the proposed plants were developed enabling future VRPP dynamic studies. In the present study the models were assumed as quasi-stationery being applied to an existing wind power plant located in the central mountainous region of Portugal aiming to assess the benefit of adding PV or other RES local generation.

II. Benefits Of The Aggregation of Different and Complementary Renewable Resources

Power production fluctuations can be divided in two categories: fast and slow fluctuations. There is a natural smoothing effect in fast fluctuations proportional to the number of wind turbine generators (WTG) [1]. Alongside with its natural smoothing, active systems can be used, till a certain extent, for the same purpose. Such systems may be implemented on the turbine control itself (e.g. pitch angle control [2]), or may be commanded from a higher hierarchical level through the use of VRPP (e.g. wind energy curtailment or usage of rotor inertia to store the additional energy brought by a wind gust as kinetic energy for later conversion, as in [3]).

The slower fluctuations are not naturally smoothed (in a country wide or control-zone scale) and imply the commitment of additional system reserves, generally supplied by non-renewable power plants. The possibility of combining PV with existent wind farms is a solution that could effectively reduce these fluctuations [4].

The installation of PV in wind farms can take advantage of the Portuguese legislation [5] that allows already existing wind farms to have 20% of installed capacity over its licensed limit (a.k.a. "overcapacity"). The possibility of using this overcapacity with PV enables the opportunity to complement the wind generation and has the potential to present a high internal rate of return (IRR) of the investment.

Like the natural cancelation of fast fluctuations in Wind generation similar behavior is expected for PV installations. Smoothing of fast power fluctuations has been reported at local scale (4 km) [6] and better results were achieved when taking into account 100 systems spread over Germany [7].

In an effort to identify simple methods to tackle slow fluctuations of wind and solar resources, the correlation of both must be evaluated. Considering the daily period, while PV depends on day light, the night period is dominant in many wind power plant generation profiles [4]. For the annual period, the complementarity is stated considering large areas in [8], [9] and [10] but none of those studies considered the integration of wind and PV at a local scale (0.5<d<50 km).

In current work we show that a hybrid wind/PV power plant is able to take advantage of the diurnal and annual cycle to diminish slow power fluctuations. This setup also favors the natural smoothing effect of the fast power fluctuations.

III. METHODOLOGY

A time–domain model in a power system simulation tool (PSS/E) was setup in order to evaluate the advantages of implementing a PV overcapacity in a wind farm. A one year data series of wind speed and irradiance in an existing wind farm site was used to feed the model.

The data input of the model is described in subsection A while the models used are described in subsection B.

A. Input data

Regarding the necessity of feeding each of the wind turbines with one wind series, a synthetic series needed to be generated. The baseline wind speed data at the hub height was measured as the average wind speed of every 30 minutes in a real wind farm site in central Portugal. The turbulence component, modeled with Davenport spectrum [11], [12], is added to interpolated wind speed for each simulation time step for each of the wind turbines as in:

$$U_k(t) = U_{30}(t) + U_{turb\ k}(t) \quad (2)$$

where: U_k stands for the wind speed time series at the WTG k, U_{30} is the interpolated measured mean speed for simulation time t and $U_{turb\ k}$ is the turbulence component of the wind speed in the time step t for the WTG k.

The global solar irradiance series to be used is a test reference year obtained for the optimal slope at the case study´s location, with a resolution of 1 hour from SolTerm [13] database. Besides their different sampling rate, both the irradiation and the wind speed data series have a length of one year.

B. Model description

The time-depending models used in this case study can model adequately the dynamic characteristics of the RES, although the phenomenon of interest in the present study is quasi-stationary. Priority was given to the use of standard models from the platform library (PSS/E).

1) WTG model

For modeling the WTG: control, generator and mechanic, standard modules (fully described in [14]) were used. Wind input and aerodynamic modules were created and used as User Modules (USRMDL). Connectivity between modules is shown in Fig.1.

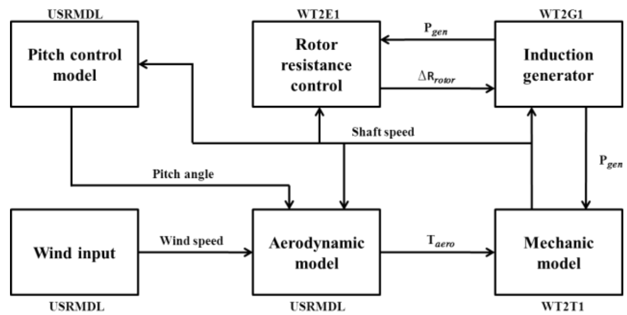

Figure 1. WTG model diagram (adapted from [14])

The turbine mechanical power output is defined [15] as:

$$P_{mec}(t) = 0.5\, \rho\, A_r\, c_p(\lambda, \theta)\, U^3(t) \quad (3)$$

where: P_{mec} is the extracted mechanical power [W], ρ is the air density[kg/m^3], A_r is the rotor swept area [m^2], c_p is the performance coefficient, λ is the tip speed ratio or the ratio between the blade tip speed U_t [m/s] and wind speed at hub height upstream the rotor U [m/s].

A simple algebraic relation was used in order to model the rotor power coefficient characteristic, based in [16]:

$$c_p(\lambda, \theta) = 0.73\,(151/\lambda_i - 0.58\theta - 0.002\theta^{2.14} - 13.2)e^{-18.4/\lambda i} \quad (4)$$

with

$$\lambda_i = ((\lambda - 0.02\theta\,)^{-1} - 0.003\,/\,(\theta^3+1))^{-1}. \quad (5)$$

where θ is the pitch angle [degree].

In order to keep the simulation stable under high wind speeds, a proportional controller for the pitch angle is used, as depicted in Fig.2.

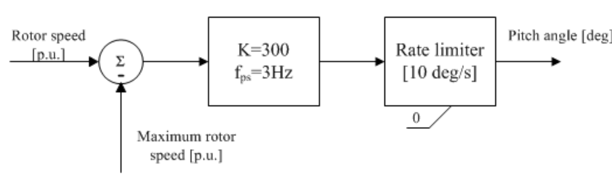

Figure 2. Pitch angle controller model.

2) PV model

The Solar PV model used simulates the performance of a PV plant connected to the grid via a power converter. As for the WTG model, preference was given for the use of standard library models [14]. In Fig. 3, the connectivity used between modules is depicted.

A PSS/E User Module is used to linearize and input a one year long irradiation series into the simulation.

The solar irradiation input is then converted linearly in a power order, following the characteristic shown in Fig. 4, by the PSS/E standard module PANEL. The power order is then sent to the electrical control module (PVEU) where the terminal voltage is considered in order to establish the active and reactive current command to the converter/generator module (PVGU) which by its turn delivers active and reactive power.

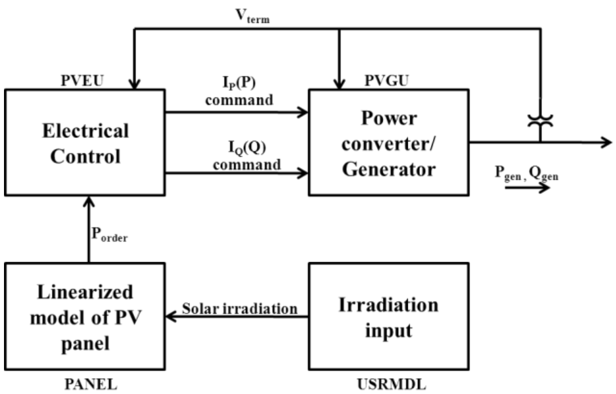

Figure 3. PV model diagram (adapted from [17])

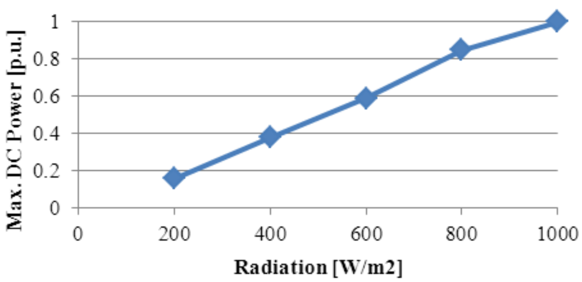

Figure 4. Typical solar panel power output characteristic

The studied wind farm grid topology is presented in Fig. 5, where four WTG (2.0 MW each) and an added PV overcapacity (2MWp) are shown.

Due to the WTG technology simulated, capacitors are added to each of the WTG terminals so as to fulfill reactive power needs. The hybrid wind farm is connected through an impedance corresponding to a short-circuit ratio ≈ 10 to the infinite bus.

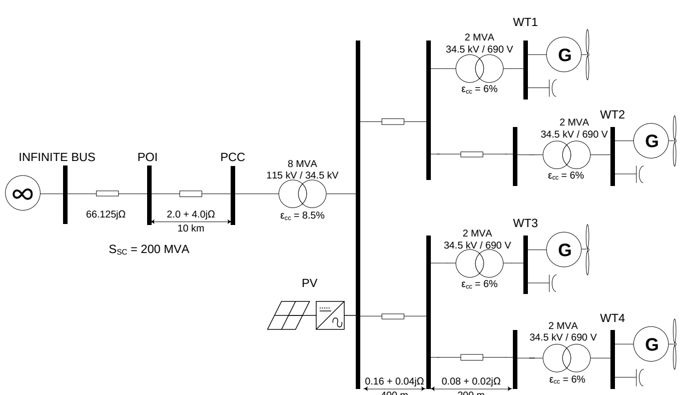

Figure 5. Hybrid wind/PV farm network diagram.

IV. Results

The hourly averaged daily profile of production obtained from the simulation and the average consumption profile for Portugal is presented in Fig.6. When comparing PV and WTG average generation profile, a negative correlation of -0.41 has been noticed, underlining their complementarity.

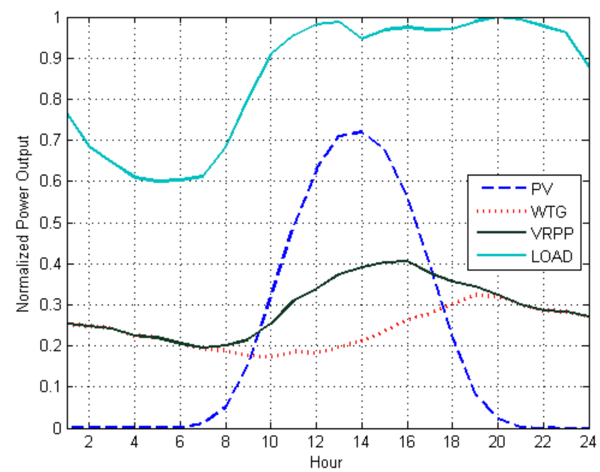

Figure 6. Average daily profile

In Table 1 are shown the correlations between the different sources and the daily profile. Data present a considerable better fit of the VRPP profile to the load profile against those of the individual sources (WTG and PV).

There is a direct immediate benefit by aggregating different renewable sources with daily profile complementarity in the efficient use of the grid connection equipment: while the capacity factor of the electrical connection infrastructure was 24.0% when only wind is connected, its capacity factor raised to 29.3% when PV generation is added.

While the connection infrastructure takes benefit from the negative correlation between wind and PV resources, their higher correlation with the load profile when combined clearly benefits the Distribution System Operation (DSO).

TABLE I. Correlation between average load daily profile and RES generations daily profiles

WTGs	0.41
PV	0.54
VRPP (merged WTGs and PV)	0.82

The normalized power for a typical day from the case study simulation is presented in Fig. 7. The increase in the capacity factor due to the PV addition is perceived as the difference between the red (WTG) and the dark green (VRPP) lines.

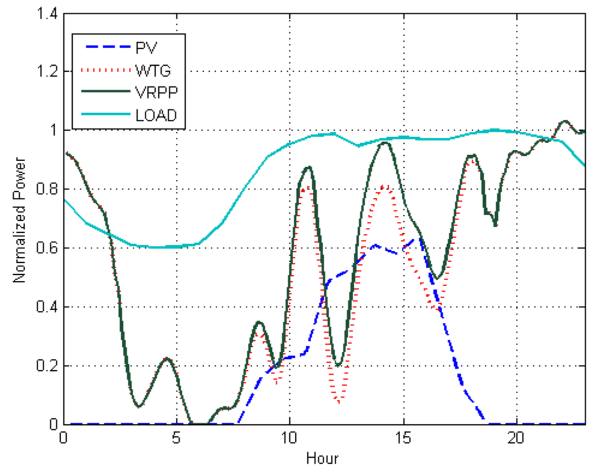

Figure 7. Power generation and load profile for a typical day

Fig. 8 compares the voltage profiles for a typical day for the VRPP with and without the PV generation. The difference between both profiles can be attributed to the additional reactive regulation provided by the PV system converter, which enhances the smoothing of voltage oscillations.

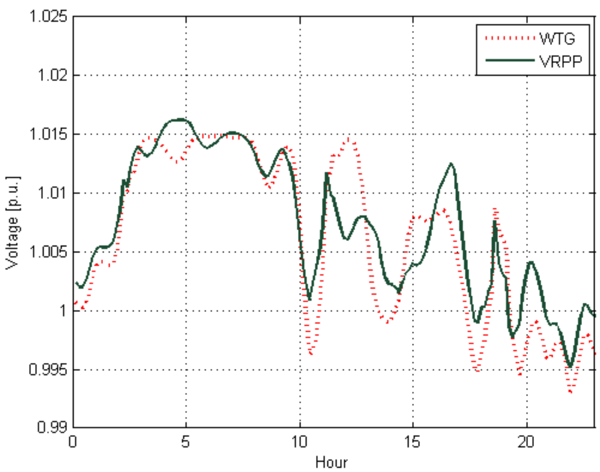

Figure 8. Voltage profile in the PCC for a typical day

The average value of the voltage and its standard deviation for the whole period simulated are presented in Table 2. Once again the VRPP configuration shows a better voltage profile, both in terms of mean voltage and its fluctuations.

TABLE II. VOLTAGE PROFILE STATISTICS IN THE PCC

	Average Voltage [pu]	**$\sigma_{voltage}$ [pu]**
Only WTGs	1.011	0.0058
VRPP	1.007	0.0033

The step changes of power produced for the pure wind farm and for the VRPP are presented in Fig. 9 and 10 respectively while their standard deviations is presented in Table 3 All of them were obtained for three time horizons: 30 minutes, 1 hour and 4 hours.

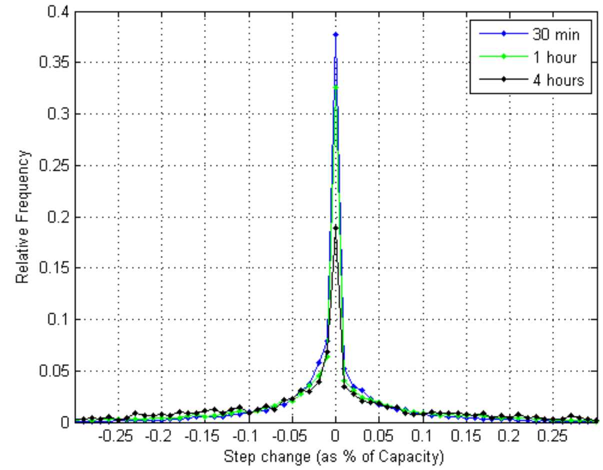

Figure 9. WTG power changes within 3 different time intervals

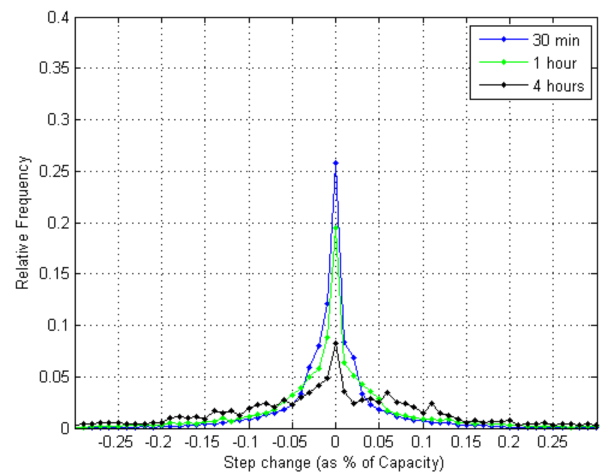

Figure 10. VRPP power changes within 3 different time intervals

TABLE III. STANDARD DEVIATION OF POWER FLUCTIATIONS

Time	**σ_{VRPP}**	**$3\sigma_{VRPP}$**	**σ_{WTG}**	**$3\sigma_{WTG}$**
30 min	0.0593	0.1778	0.0729	0.2188
1 hour	0.0936	0.2809	0.1147	0.3442
4 hours	0.1530	0.4589	0.1830	0.5489

The value of the energy is strongly dependant on the period of the day it is delivered to the power system and it is difficult to quantify. In Portugal the independent producer's tariffs are fixed and not negotiated in the Iberian market, being the added costs supported by an "energy fund". With the objective of assessing the possible economical benefit for this fund of optimizing the technical, and consequently, the economic performance of wind parks, the final client tariff in Portugal was taken as a baseline and therefore the energy yield was divided in three distinct hour ranges: "peak load hours", "standard load hours", and "no load hours". For the simulated year, the energy yield for a wind park and a VRPP was categorized by its production hour and is presented in Table 4.

TABLE IV. ENERGY PRODUCED

	Peak hours [GWh]	Std. hours [GWh]	No load hours [GWh]
Only WTGs	3.10	6.92	6.80
VRPP	3.57	10.10	6.85

A relation between the final client tariff and the mean tariff paid in 2010 for wind energy is presented in Table 5.

TABLE V. TARIFFS

	Peak hours	Std. hours	No load hours
Final Consumer Tariff	263.9 €/MWh	137.6 €/MWh	69.1 €/MWh
Tariff [adim.]	1.9179	**1.0**	0.5022
Eq. Wind Tariff	175.7 €/MWh	91.6 €/MWh	46.0 €/MWh

Table 6 presents the expected economic benefit of the VRPP for the simulated year. Additionally, the revenue from the installation of a 2 MW battery energy storage system (BESS) was accessed. The considered BESS has 80% efficiency in the charging/discharging cycle and a control strategy of charging in the no load hours and supply only the morning peak hours (capacity of 3MWh) or all the peak hours (capacity of 8 MWh).

TABLE VI. REVENUE AND INCREASED BENEFIT

	Revenue [€]	Potential benefit (€)
WTG	1 490 879	-
VRPP	1 866 588	375 709
VRPP + BESS (3 MWh)	1 998 512	507 632
VRPP + BESS (8 MWh)	2 218 384	727 505

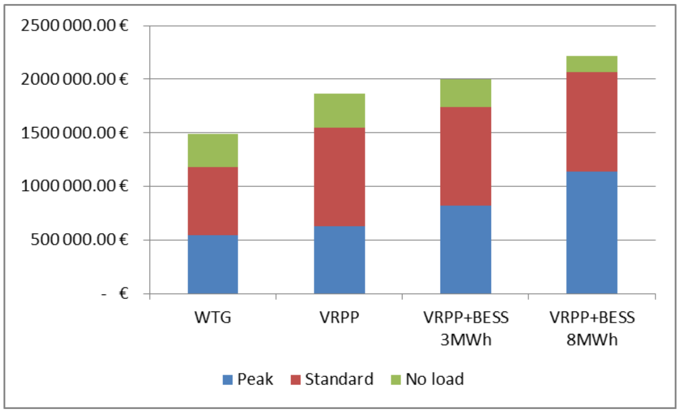

Figure 11. Revenue composition for the discussed cases.

V. CONCLUSION

A case study developing the Virtual Renewable Power Plant (VRPP) concept was carried out taking advantage of the Portuguese legislation to install 20% of overcapacity in wind farms. This paper aimed to evaluate the addition of PV overcapacity, instead of using the common approach of installing more turbines. A time domain model with typical reference data series was used to simulate a hybrid Virtual VRPP and assessing its advantages in terms of the local grid power quality and the power plant revenue.

Several positive impacts both for RES developers and to the system operators were identified. For the developers, the result of adding 2 MWp of PV to an 8 MW-wind plant is a direct increase from 24.0% to 29.3% in the capacity factor, for the same electrical infrastructures, resulting in a 25% revenue increase. A revenue increase of 48% could be achieved through the addition of a 2 MW/8 MWh BESS. Moreover, from the system's management point of view, the combined VRPP daily production profiles correlates much better with the average daily load profile (0.82) than WTG (0.41) or PV (0.54) alone.

The voltage fluctuations (that have a direct impact in local grid power quality) were characterized at the point of common coupling with the existing grid (PCC). The results obtained show an added smoothing effect in the hybrid VRPP voltage's fluctuation ($\sigma_{voltage}$ = 0.0033 pu) when compared to the standard initial wind plant ($\sigma_{voltage}$ = 0.0058 pu). Power fluctuations were also smoothed: for instance, hourly standard deviation was reduced from 0.1147 (WTG) to 0.0936 (VRPP).

Further studies on the VRPP concept including RES units with some power regulation capability (such as biomass or concentrated solar power - CSP plants); the power quality issues (such as flicker and the harmonic distortion); as well as a detailed economic analysis should be developed to assess the full potential of these combined virtual plants. Still, the current work enables to conclude on the VRPP economical (through a clear increase in the capacity factor and revenue) and technical (a reduction of the voltage fluctuations) advantages in similar situations where the characteristics of the RES resources are complementary.

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