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Field Tests for the Provision of Frequency Containment and Frequency Restoration Reserve by Variable Renewable Energy Sources Virtual Power Plants

Andrea Michiorri, Andreas Liebelt, Andreas Linder, Georges Kariniotakis, Lina Ruiz, Marine Joos, Nicolas Girard, Peng Li, Simon Camal, Stefan Siegl

***Abstract*-- This paper presents the results of a series of tests on the provision of ancillary services by a Virtual Power Plant composed of variable Renewable Energy Resources. The ancillary services provided are Frequency Containment Reserve and Frequency Restoration Reserve, roughly primary and secondary reserve, and the resources used by the virtual power plant were wind and photovoltaics plant for a total of 273 MW of installed power on 17 generators. Renewable dispatchable units such as batteries, hydro or biomass were not considered in order to quantify the performance with the most critical generation technologies. Symmetric reserve activation of up to 10 MW. The quality of the reserve delivery was measured according to purpose-developed metrics and telecommunication failures were considered the main source of errors.**

***Index Terms*-- Virtual power plant, Ancillary services, Reserve, Renewables, Wind power, Photovoltaics**

NOMENCLATURE

AAP : Available Active Power
aFRR : automatic Frequency Restoration Reserve
AS: Ancillary Services
CS: Control System
FCR : Frequency Containment Reserve
mFRR : manual Frequency Restoration Reserve
PP: Power Plant
PP: Power Plants
PV : Photovoltaic
RES: Renewable Energy Sources
RTS: Real Time Schedule
TSO: Transmission System Operator
VPP: Virtual Power Plant
vRES: variable Renewable Energy Sources

I. INTRODUCTION

Ancillary services are crucial for the safe operation of electrical power systems. Traditionally these services were provided by thermal or hydro dispatchable Power Plants (PPs). But the growing penetration of variable Renewable Energy Sources (RES) such as wind or photovoltaics encourage the development of technologies and approaches to allow them to provide these services. Renewables can account for roughly 46% of the installed capacity in Europe [1], with wind and solar representing respectively 17% and 13% and the rest made by hydro. On one hand, such common technologies should also be able to support the power systems where they are connected on their road to technological maturity. On the other hand, not doing so, would reduce the revenue of renewable power producers when these services are remunerated.

This manuscript presents the results of field tests carried out within the framework of the European project REstable aiming at showing the potential of a variable Renewable Energy Sources (vRES) based Virtual Power Plant (VPP) to provide Ancillary

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Services (AS) to the Transmission System Operator (TSO). In particular, the AS products tested are: Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR), and manual Frequency Restoration Reserve (mFRR). Detailed definitions for these products are provided in Section III. A.

Although the objective is to present the results of the field tests, a little introduction is given about the rest of the project to put it in context and address the reader to additional sources presenting other results which are linked to this. The approach followed is the VPP. The reasoning behind this is that a single vRES plant cannot propose a reliable amount of production for AS, especially considering their sensitive nature, without recurring to additional tools such as thermal generators or batteries. On the contrary, thanks to a VPP, it is possible to exploit the reduction of production correlation with distance as shown in [2] and [3]. For the tests it was possible to choose among a large portfolio of thirty-three wind and PV PPs for a total of 429.9 MW in Germany and France and a subset of 17 generators for a total of 273MW was used for the tests. The main limitations are the telecommunication infrastructure present on site and the need to limit the amount of energy curtailed during the tests. It was explicitly decided not to introduce in the portfolio batteries, biomass or hydro generators: the objective was to prove the concept and understand the potential and limits of a vRES VPP and not to try to achieve the maximum volume of AS provided during the tests.

An overview of the VPP is shown in Fig. 1. Here it is possible to see the VPP Control system (VPP-CS) communicating directly with data concentrators in the plant's operators' premises. From here the signals are sent to the individual power plants through the operator's network of choice. Finally, within the power plants, orders are issued to the individual turbines by the plant control system and then to the turbine control system. Measurements from the field (power, weather) come back to the VPP-CS through the same route. The Fig. shows also the location of the Wind and PV farms used in the test.

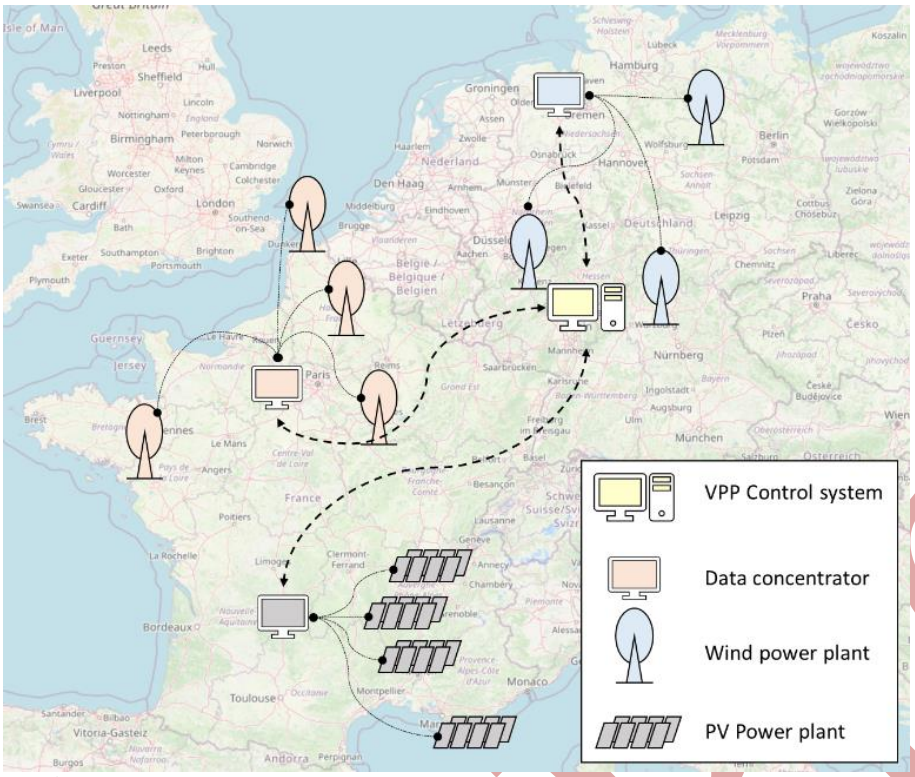


Fig. 1: Physical architecture of the VPP

A. State of the art

vRES AS provision capacity becomes more important with the increased penetration rate of renewables into the European power system, pushing research on this area in the recent years. The existing organisation is suboptimal since it has been designed for a power system supplied exclusively with dispatchable thermal or hydro generators. This results in additional costs suffered by the whole power system for the integration of renewables, as argued in [4] and [5]. Furthermore, current rules impact bidding strategies as shown in [6] distorting optimal market results.

For this in recent years it has been proposed to encourage renewables to provide ancillary services to network operators. In [7] the necessity for improving current regulation is highlighted whilst in [8] it is shown how coordinated wind farms can offer services such as temporary frequency response and power oscillation damping for different level of penetration, but it highlights also the necessity of the coordination among them.

A quantification of the benefits arising from wind farms provision of ancillary services has been proposed in [9], where the provision of primary reserve has been simulated and overall system generation cost has shown considerable reduction, with benefits comparable to the ones obtained with a large 100MW energy storage.

As mentioned above in [7] regulatory and market design changes are necessary to allow the provision of ancillary services by wind farms. Theoretical solutions have been proposed in [10] where an optimal design for an electricity market including wind farms has been proposed sowing sensible gains in terms of revenue for the wind farm producers. In [11] the problem of optimal European integrated market design for integrating wind-based ancillary services is faced. Finally, a critical evaluation of current approaches in Nordic countries and Australia is presented in [12] and [13] respectively.

In general, most studies face this problem when considering fully renewable power systems or power systems with large vRES penetration rates, but often the AS provision is delegated to dispatchable plants or energy storage.

In particular [14] analyse the potential of the Swiss power system to reach a 40% renewable penetration rate mainly from wind and PV. Through simulations, it is shown that the large presence of hydro and pumped hydro plants will be able to cover the AS needs. In a similar work carried out on a generic IEEE 118 bus network [15], it is shown that a vRES-VPP, co-adjuvanted by pumped hydro and energy storage can achieve higher returns by participating in energy and AS markets. The same problem is faced in [16] where attention is paid to the robustness of the unit commitment in presence of large wind ramps.

In the cases above, storage or pumped hydro are considered the flexibilities necessary to maintain stability and absorb the fluctuations from vRES. But another possible approach consists in obtaining the necessary flexibility to be extracted directly from the installed vRES capacity through virtual inertia [17] for wind and PV plants. Examples of this can be found in [18], where flexible PV plants, capable to provide AS with storage and proactive curtailment, are used to provide a secondary reserve, resulting in lower dispatching costs for the Italian system. The problem has also been explored in [19] where strategies for the multiple offers of energy and AS from wind PPs are devised.

Finally, it can be mentioned the very recent [20] where the use of wind farms for the provision of ancillary services is proposed.

B. Contributions and structure of the paper

The paradigm followed by current research implies the quantification of the variability given by vRES and its management through other technologies such as conventional thermal units, batteries, and pumped hydro. Nevertheless, the idea that vRES can contribute to the stability of the system is taking place.

In this topic, this manuscript aims at bringing the following contributions to the power system community:

- The description of an architecture allowing vRES-VPPs to deliver AS
- The evaluation of large-scale field tests showing its performance
- The definition of evaluation criteria for the quality of AS provision, applicable to vRES or other types of generators and VPP.

This paper is structured as follows: after an introduction in Section I where the context, the state of the art and the contributions are presented, the core of the work is divided into two parts. The architecture of the AS provision is described in Section II whilst tests are described in Section III. Finally, a discussion of the concept and the results is presented in Section IV. IV and conclusions are drawn in Section V.

II. Architecture



Fig. 2: The three steps preceding reserve activation: predictions and participation in markets.

The architecture of the approach proposed for the provision of AS from a vRES-based VPP, shown in Fig. 2, can be divided into three steps:

1. Firstly, day-ahead production forecasts are calculated and used to quantify the reliable fraction of the vRES-VPP production to be proposed as AS or to be sold as energy. More details on this research can be found in [21]–[23].
2. Secondly, the forecasts obtained in the previous step are used to suggest optimal bids to the AS and energy markets, by taking into account expected price spreads, expected production from the previous step, the technical characteristics of the different products and risk aversion. Examples of this can be found in [21], [22].
3. Finally, if the VPP is called to deliver a service sold at the previous step, a CS issues the setpoints necessary to provide the agreed upward or downward flexibility to each component of the VPP. This is done by supervising the effective and expected available production. Detail on this step can be found in [23].

It will be given here space to a description of the third step, particularly relevant to this work, whilst the reader is referred to the papers above for the previous two steps.

A. Real time dispatch

The calculation of the AS setpoints, in its most complete version can be described as in Fig. 3 and reported in the steps below:

1. Firstly, the flexibility of each PP is assessed. This is obtained by calculating the Available Active Power (AAP), removing a safety off-set, and dividing by half the remaining value.
2. Then an economic merit order is calculated using the marginal cost from each power plant. In fact, although the marginal cost for vRES power plants can be considered null, there are considerations which assign to each one of them a different priority, such as different contractual obligations or different prices for power purchase agreements.
3. Finally, the flexibility is dispatched to the generators: in order to provide positive and negative flexibility of a value ϕ, the generator is pre-curtailed of $\phi/2$ through all the period.

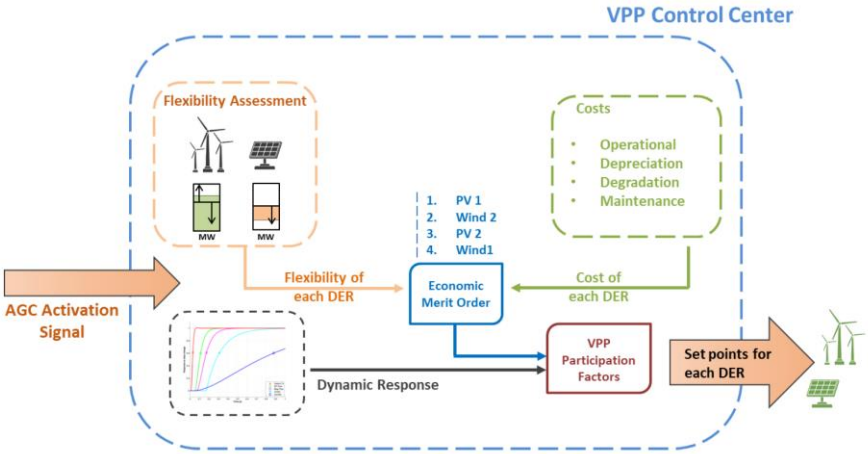


Fig. 3: VPP-CS scheme

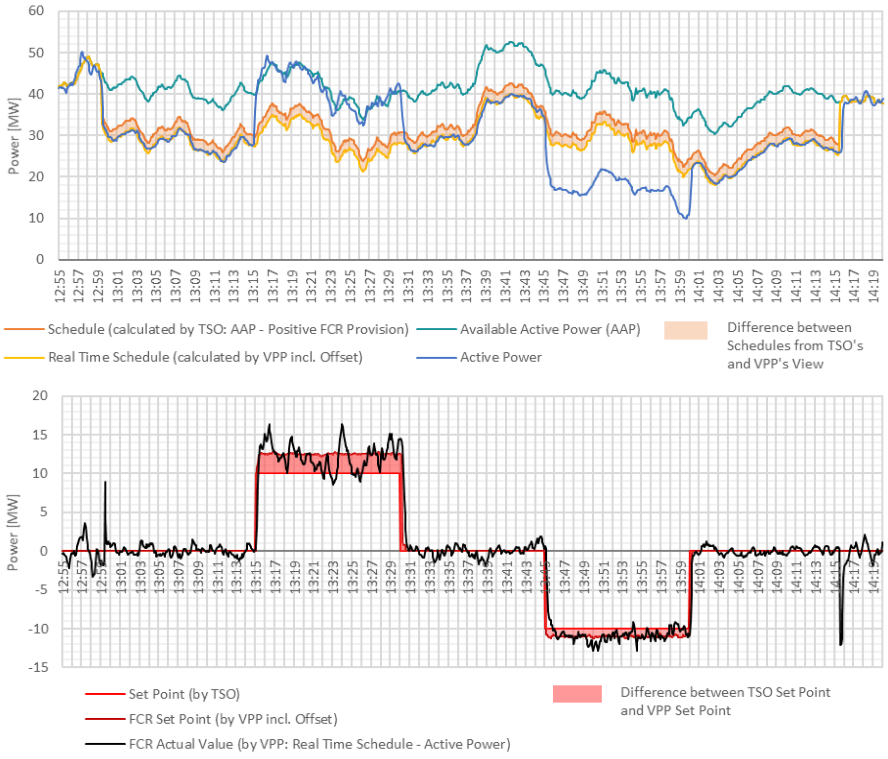


Fig. 4: Flexibility dispatch, absolute (above) and relative (below).

This last point can be intuitively seen in Fig. 4, where the curtailment during a test is shown in absolute (above) and relative (below) values. It is possible to see the AAP of the combined VPP, the setpoint from the TSO (in this case for aFRR), the setpoint offset with the actual schedule by the VPP and the resulting active power from the VPP. The relative view below, shows clearly how the VPP managed to provide a positive and negative step when asked.

The yellow shaded area in Fig. 3 represents an additional improvement where the merit order is enriched by estimations of the speed of response of the generators. For example, inverter-connected PV farms are faster than wind farms, and smaller wind farms with less inertia can be faster than larger ones. This approach could allow for improved precision and quality of the AS delivery at the expense of the use of potentially more expensive generators.

III. Tests

A. *Definition of the perimeter*

Regarding the power plants used in the tests, the following criteria have been followed for their selection:

- Geographical distribution. Presence in different climatic regions to reduce the correlation. In particular, as shown in Fig. 1, wind farms were available in the area of the North Sea and the Atlantic Ocean, whilst PV plants were available in southern France. It was desired also a presence in the area of different TSO and countries.
- Resource. In order to reduce the correlation of renewable power production the presence of plants exploiting different renewable resources is necessary. Therefore, wind and solar power plants must be part of the demonstration.
- The demonstration implies production curtailment, with a resulting loss of revenue for the plant operator. In order to limit this cost, a maximum amount of curtailed generation has been fixed to 80 MWh.

As a result of these criteria, a subset of 17 generators for a total of 273MW has been selected as summarised in Table I.

TABLE I Composition of the VPP in MW of installed capacity and, in brackets, in number of plants

Resource	**France**	**Germany**
Solar	8.7 (4)	
Wind	98.4 (9)	166 (4)
Tot	107.1 (13)	166 (4)

Regarding the AS tested, the attention has been focused on the following types of reserve involving the alteration of active power from the VPP:

- Frequency Containment Reserve (FCR)
- automatic Frequency Restoration Reserve (aFRR)
- manual Frequency Restoration Reserve (mFRR)

A quick description of the technical characteristics of these services is provided below. These definitions are based on the practice in Germany, France and Portugal, which are anyway aligned to the ENTSOe practices.

FCR is the fastest active power reserve which is available in the central European electricity system with a full activation time of 30 seconds and a minimum response time from 5 to 15 seconds according to the country. Its activation is decentralized as a function of the grid frequency measured at the plant level. In total 3000 MW of positive and negative FCR capacity are procured for the synchronous European network by each TSO according to a predetermined share determined on the annual consumption in its control area. At the time of the tests, FCR was contracted indefinitely in France and Portugal and had a 1-week length in Germany.

FRR is divided by the European Commission Network Code [24] into two categories: automatic and manual FRR. In the first case, aFRR, it is activated with a feedback control by the TSO, whilst in the second case, mFRR, the activation is decided by the operator. They can have different activation timeframes, usually in the fraction of milliseconds for the automatic and 5-7 minutes for the manual, with a full activation within 15 minutes. Harmonisation is expected at the ENTSOe level [25].

RR is activated manually, with a minimum response time of around 5 minutes, and is less standardised among different countries. In particular it must be noted that in Germany this service is not present and in France, voluntarily production curtailment is not allowed for plants under public purchase agreements. Also, in France, it is possible to group the response of several power plants.

Anyway, this aspect is evolving with the creation of a single market for FCR procurement implying a standardised definition for this product [26]. A summary table with definitions for the timing of these services can be found in Table II.

TABLE II summary table for different type of reserves activation times

AS	**Minimum delay**	**Maximum delay**
FCR		5-15 secs
aFRR	30 seconds	5 Minutes
mFRR	5 mins	12.5 Minutes
RR	12.5 mins	60 minutes

Finally, to evaluate AS quality response, an analysis of the German grid code and the three German TSOs qualification requirements has been carried out, leading to the definition of a series of quality criteria summarised in Table III. For each one of the three AS, the criteria have been divided into three categories: Provision (P), Activation (A) and Economy (E). These quality criteria were then implemented in an extension of the VPP-CS to calculate analytically the performance of the tests.

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B. Evaluation metrics

The values within the fulfilment corridor are one main metric to determine a KPI regarding the activation quality. The fulfilment corridor is determined for each time stamp by the upper border to over-fulfilment and the lower border to under-fulfilment and considerate positive and negative tolerances as well as ramp-up periods. The quality of the activation is measured by the share of actual values, which are within the fulfilment corridor.

Considering this, and the measurements available with a 2-3 seconds frequency according to the plant, it is possible to calculate two main metrics: Activation Quality and Provision Availability.

- **Activation Quality** is measured as the share of times that the Active Power falls within the fulfilment corridor. In this definition, every under or fulfilment is considered equal independent of its magnitude.
- **Provision Availability** is measured as the share of time that the Available Active Power is higher than the Ordered Provision.

These two parameters can then be calculated for Positive and Negative reserve provisions and the overall test.

C. The architecture of the tests

Tests have been carried out during the winter of 2018 and were characterised by two aspects.

Firstly, in the case of FCR, the signal is measured only at the VPP-CS and not at each power plant as is the case usually with FCR. This means that the whole VPP react as a single unit and not as different plants scattered on the grid. During the tests, a "frequency meter emulator" was used to start the activities. This was done since the test platform is not completely automated and a series of human decisions were necessary to start them.

TABLE III CRITERIA DEFINING FCR, AFRR AND MFRR QUALITY REQUIREMENTS

		Short title	Description
FCR	**P**	Provision time slice	The VPP must provide the contracted FCR for the whole time slice of one week from Monday 0:00 to Sunday 24:00.
		Provision availability	The VPP must ensure a 100% availability of contracted power during the whole provision period. The provision of FCR must be activated before the beginning of each time slice.
	A	Activation time	The VPP must activate the required power reserve within max. 30 seconds.
		Gradient	The VPP may reach the set point signal via an immediate step response. Additionally, the rate of change of power has to be agreed upon with the TSO. The VPP has to activate the FCR evenly, e.g. the first 50 % in the first 15 seconds.
		Duration of activation	The VPP must be able to deliver the contracted FCR for at least 15 minutes.
	E	Over- and under-fulfilment	The VPP must ensure a maximum over-fulfilment of 5 MW or 20 % of the set point and avoid any under-fulfilment.
		Loss of Energy	The VPP should cause a minimum loss of energy during the provision and activation of APR.
		Contract sanctions	The VPP should avoid possible penalties caused by repeated outages, under- or over-fulfilment and extra costs due to more expensive FCR products which have to be procured by the TSO.
aFRR	**P**	Provision time slice	The VPP must provide the one-day-ahead contracted aFRR for the whole day separated into six-time slices of each 4 hours.
		Provision availability	The VPP must ensure a 100% availability of contracted positive and negative power during the whole provision period.
	A	Activation time	The VPP must activate the required power reserve within max. 5 minutes.
		Reaction	The VPP must show the first reaction to a changing set point within max. 30 seconds.
		Minimum gradient	The VPP must follow a dynamic gradient depending on the set point progress, which is given by the required power change divided by 270 seconds.
	E	Over-fulfilment	The VPP must ensure a maximum over-fulfilment of 5 MW or 10 % of the set point.
		Tolerance channel	The VPP must provide the APR at any time within the acceptance channel with appending tolerance of ± 5 % of the set point.
		Penalties for under-fulfilment	The VPP must stick to the lower tolerance value of 95 % of the set point to pay no penalties.
		Loss of energy	The VPP should cause a minimum loss of energy during the provision and activation of APR.
		Billable energy amounts	The VPP should generate an accepted and billable energy amount as high as possible.
		Contract sanctions	The VPP should avoid possible penalties caused by repeated outages, under- or over-fulfilment and extra costs due to more expensive aFRR products which have to be procured by the TSO.
mFRR	**P**	Provision time slice	The VPP must provide the one-day-ahead contracted aFRR for the whole day separated into six-time slices of each 4 hours.
		Provision availability	The VPP must ensure a 100% availability of contracted positive and negative power during the whole provision period. Technical units whose availability is below 100% may only be prequalified within an mFRR cluster.
	A	Activation time	The VPP must activate the required power reserve within max. 15 minutes.
		Over- and under-fulfilment	The VPP must ensure a maximum over-fulfilment of 20 % of the set point and avoid any under-fulfilment.
	E	Maximum remuneration	For a maximum APR remuneration, the VPP shall provide preferably exactly 100 % of the set point.
		Loss of energy	The VPP should cause a minimum loss of energy during the provision and activation of APR.
		Billable energy amounts	The VPP should generate an accepted and billable energy amount as high as possible.
		Contract sanctions	The VPP should avoid possible penalties caused by repeated outages, under- or over-fulfilment and extra costs due to more expensive mFRR products which have to be procured by the TSO.

This refers only to the field tests and not to an application in real operating conditions.

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Secondly, a common schedule of positive and negative reserve activation was created for the three types of reserve tested. The results were then evaluated against the quality metrics defined for the individual AS. This allowed us to extract more information from a single test. The schedule starts by bringing the VPP in pre-curtailment to be able to provide the upwards flexibility demanded.

It is then followed by three 20 minutes periods of constant production, separated by two 20 minutes, 5 MW upwards and downwards steps.

Initially, a longer schedule involving also ramp response and real response following an Automatic Generation Control (AGC) signal was prepared, to make this test the most possible similar to the pre-qualification tests required in Germany at the time. Anyway, the last two parts were removed to reduce the length of tests, perform more of them, and focus on the step response which is the most critical part, with the logic that the performance of the final parts would have been better than the performance of the first. An example of this can be seen in Fig. 5.

D. Results

A total of six full tests were carried out in the winter of 2018. Examples can be found in Fig. 6 and a summary of the results can be found in Fig. 7.

Fig. 6 shows the behaviour of the combined response from the VPP in two different tests, #2 and #3. This comparison is presented to show visually the behaviour of the VPP in presence of different machines. In the upper example (Test #2), a larger volume of the reserve is tested, but the oscillations of the VPP response are far wider than in the example below (Test #1). The reasons for these differences have been identified in the:

- the different types of turbines and turbine control systems, with higher inertia or slower response time.
- imprecision in the calculation of the AAP.
- latency of the telecommunication lines

Anyway, more recent turbines with fibre optics telecommunications as the ones involved in Test #1 or Test#5, provide very high performance. Of the three problems mentioned above, latency can be fixed by a simple upgrade of the line and AAP estimation precision can be improved at the algorithmic level or by fixing/modifying wind speed sensors at the turbine or plant level.

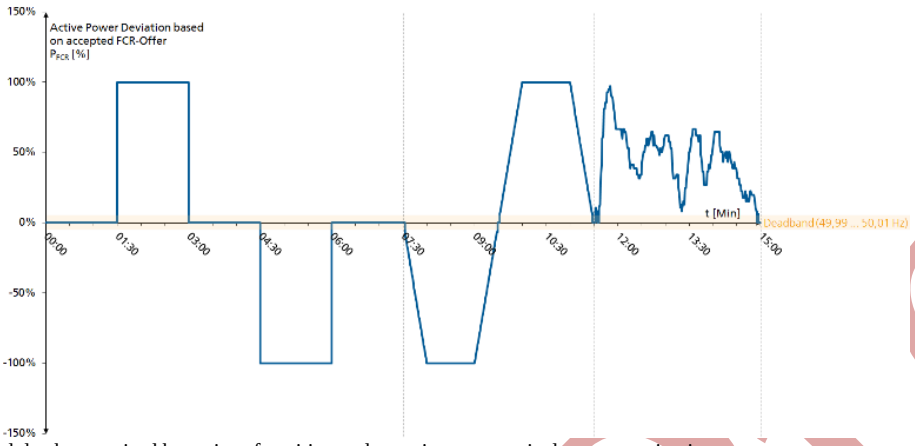


Fig. 5: General test schedule characterised by series of positive and negative symmetrical reserve activations

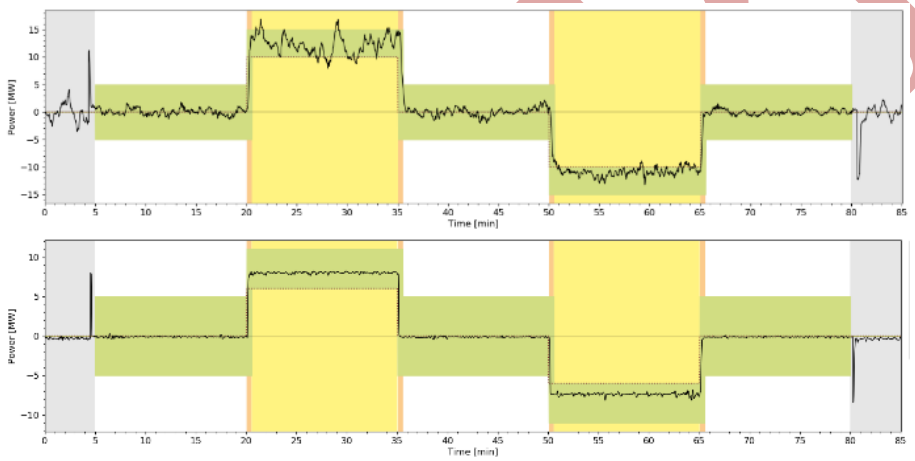


Fig. 6 : Comparison of two tests: #2 (above) and #1 (below) according to the tolerance corridors for FCR.

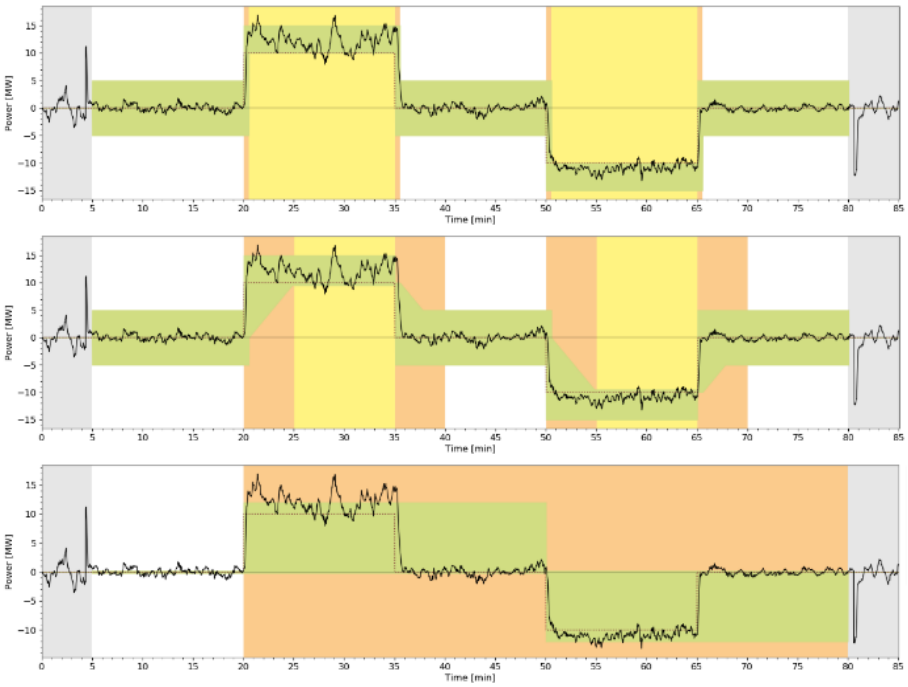


Fig. 7 : Fulfilment corridor for FCR (above), aFRR (middle) and mFRR (below) during the 3rd full-test of the VPP

Fig. 7 on the contrary, presents the results of Test #2, evaluated with the different tolerance bands for the three types of reserve considered. This test has been chosen because the large variability of the response shows better the excursions outside the tolerance areas explaining the different quality scores according to the reserve product considered. In the case of FCR, it shows that the system is able to provide a very fast response, in line with the requirements, whilst it can be more difficult to maintain the production at a constant level. The same can be said for the other reserve products which allows for a slower response from traditional power plants with higher inertia.

Table IV shows a summary of the quality metrics for the six tests. A detail that emerges from this comparison is the fact that the score for 'activation' is often lower than 'provision' meaning that in most of the cases, problems are not given by a lack of resource, but by issues in the control chain. In both cases, the performances are influenced by AAP estimation errors. Finally, it must be remembered that in each test, the volume of the flexibility provided changes according to the size of the VPP and the availability at the time of the tests.

TABLE IV QUALITY ASSESSMENT OF THE PROVISION OF THE RESERVE FROM THE RENEWABLE-BASED VIRTUAL POWER PLANT

Test	KPIs [%]	1	2	3	4	5	6
FCR	Activation	91.3	83.1	69.6	94.1	100.0	79.1
	Provision	95.9	90.7	94.7	95.6	100.0	60.7
	Sum	93.7	87.1	82.7	94.9	100.0	69.6
aFRR	Activation	97.3	96.2	81.9	96.2	99.7	91.2
	Provision	98.3	87.8	94.8	96.7	100.0	69.3
	Sum	97.5	94.7	87.7	96.5	99.8	87.1
mFRR	Activation	52.6	75.8	78.6	59.0	57.5	-
	Provision	-	-	92.8	100.0	100.0	-
	Sum	52.6	75.8	81.3	66.6	65.4	-

IV. Discussion

The experience gathered in this project and in particular during the test phase allows us to draw several conclusions:

Firstly, that vRES-VPP can provide upward and downward reserve with acceptable performance, arriving at up to 100% availability.

Secondly, that contrary to prior beliefs, control issues and not resource availability are the main causes of performance degradation. This can be seen from the fact that older generators with slower control systems or older telecommunication provide the worst performance, whilst newer generators built for finer control can provide an almost perfect response. For this, the reader can compare the response quality of two generators in Fig. 6, with the upper chart referring to an older wind turbine type and the lower chart referring to a more performant control system and telecommunication connection.

How can this be interpreted, and what are their consequences?

- vRES-VPP reserve quality provision, constrained mainly by control and telecommunication, has the potential to have the same quality as other distributed flexibility resources such as storage, diesel-VPPs and demand-response.

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- In general, existing vRES power plants can be integrated into similar VPP-CS with minimum hardware investment

Other considerations arise about other aspects of the AS provision by vRES, suggesting further areas of investigation, not presented in this document. The most important ones are summarised here.

Intermittency and reliability. The first issue to overcome is represented by the intermittency of the resource used and, the possibility, to use it for critical services such as FCR and aFRR. The tests described here show that within the period of a single delivery, quality problems don't come from the availability of the resource, but mainly from the control system and one of its crucial inputs, the AAP estimation. Regarding the reliability of the delivery, it could also be argued that spreading the response on a larger number of plants, would reduce problems in case of outages in one of them. On the other side, considering the control or communication outage probability, this would make the system more exposed to outages in some sections. In definitive, specific studies should investigate this problem, both in terms of the minimum power achievable from large vRES VPP and in terms of the dependence on telecommunication and reliability in presence of telecommunication outages.

vRES curtailment. Another issue that often arises is the fact that with this approach, the VPP vRES production must be pre-curtailed in the time slots when the reserve has been awarded. This can be seen as a waste of resources, reducing the overall capacity factor of the plants. Anyway, the power plants currently providing reserve, don't work at full capacity factor, and it is rare that even for hydro or thermal power plants not providing reserve, the capacity factor reaches the unity. Another consequence of the pre-curtailment is in the cost of AS provided in this way. Although the cost of activation would always be roughly proportional to the electricity price at the time of activation, the reserve price would also be proportional to this value, making these offers uncompetitive concerning the reserve proposed by conventional thermal plants. This may mean that AS provision by vRES becomes attractive only in a condition of low or negative prices. In the alternative, vRES may have to be allowed to provide only downward regulation, reducing the need for pre-curtailment. Again, specific studies must be carried out on this.

Impact on market prices. It has been highlighted also that such an approach, by allowing a large volume of installed capacity to participate in AS markets, would modify their behaviour and reduce prices. More critically, in the case of vRES, it would be difficult to differentiate between the part of production allocated to the energy that allocated to reserve, resulting in a critical lack of both in case of a sudden drop of resource. The authors believe that this is a possible problem and that should be tackled at the step of market design.

This works defines also further areas of investigation. In particular, the existence of valid alternatives to the approaches used in the work, such as: 1) The whole proposed architecture based on a pre-curtailed vRES VPP, 2) The quantification of the available AS volume, carried out though forecasts based on numerical weather predictions, 3) The definition of optimal bids for the sale of the different products in their respective markets, carried out as a stochastic optimisation, 4) The control scheme for the dispatch of the reserve activation, based on a purely economic merit order.

Furthermore, the field tests suggest also more precise areas of research such as AAP estimation and the definition of criteria for reserve quality provision. In the first case it has been shown that errors in AAP estimation are behind most of the quality issues identified. vRES PP are often equipped with AAP sensors provided by the manufacturers for performance monitoring, but there are not necessarily conceived for the monitoring at the resolution required for AS provision. Innovative solutions may have to take into account the fast variability of the response, the inertia of the system or wake effects in the case of large wind plants. In the case of the definition of the quality of the reserve provision, the problem is different: currently, relatively large tolerance corridors are permitted in order to allow slower generators to ramp up and down to the desired target. In the case of vRES, it has been shown that this is not a problem because of the very fast response. On the contrary, it has been observed a relatively large intra minute oscillation around the control targets. Therefore, tolerance margins could also be narrower if the excursion out of the tolerance areas are limited in magnitude and time, and recovered in the following seconds and minutes. Anyway, also for this, specific research is needed.

The use of storage in combination with vRES is open to investigation. This was explicitly not tested during the project, to measure the performance of older and newer generations of power plants and verify the feasibility of upgrading them with minimum investments in hardware. Anyway, at least two advantages can be imagined by integrating batteries into the mix controlled by the VPP-CS. Firstly, the quality of the response could be greatly improved, also for older plants, with the use of the fast response of a battery. Secondly, it could reduce and smooth control orders sent to the individual generators extending the lifetime of the actuators. Such a battery would have a reduced energy capacity concerning the size of the VPP and the energy displaced by the reserve since it should only absorb power oscillations. Furthermore, it can also be placed anywhere, under the control of the VPP-CS and potentially within one of the controlled power plants. It must be noted that the nature of the VPP would make straightforward the integration of distributed Energy Storage Systems, such as electric vehicles.

Finally, interesting is also the integration of demand response, which would remove the necessity to pre-curtail renewable production in order to provide upward flexibility.

V. Conclusions

The provision of ancillary services from renewable power plants is an interesting area of research and industrial application, becoming more important with the growth of the renewable penetration rate into power systems.

This manuscript presented the results of large-scale field tests carried out over a VPP made of 17 wind and PV generators for a total of 273MW. The objective of the tests was to verify the concepts and measure the quality of the reserve delivered, by making the generators perform a test inspired by pre-qualification tests required for generators to offer this type of reserve. The results

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show that the concept is sound, with successful reserve activations of up to 10 MW, and more importantly, they let to understand the necessary areas of improvement and the sources of troubles. In particular, these have been identified in generators' inertia, errors in the estimation of the Available Active Power used in real-time control, and latency in telecommunications. The system applied to newer wind turbines with state-of-the-art control and telecommunication shows results with the maximum possible score for quality.

The manuscript introduces also a possible scheme for allowing AS and energy to be provided to the markets made of three steps: forecasting resources, creating optimal bids, and then dispatching them when activated. For each one of these steps, solutions are proposed and references to relevant literature, also developed within this project, are provided.

Finally, a discussion presents several considerations relative to this concept, related to the availability of the resource, the necessity of curtailing renewable generation, the cost of this solution and the impact on the markets for services and energy. Also, the need for further research on the different topics covered, notably: proposing alternative solutions to the VPP for the provision of AS by vRES, quantifying the available volume for AS that can be provided by vRES, suggesting alternative approaches to optimally allocate AS and Energy from the VPP, suggesting improved control schemes for the dispatch, estimation of the AAP and defining methods to quantify the quality of provision.

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VII. References

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