Statistical Correlation between Wind Penetration and Grid Frequency Variations in the Irish Network

Muhammad Adeen, Guðrún Margrét Jónsdóttir, *Student Member, IEEE*, and Federico Milano, *Fellow, IEEE*
AMPSAS Laboratory, School of Electrical & Electronic Engineering, University College Dublin, Ireland
{muhammad.adeen, gudrun.jonsdottir}@ucdconnect.ie, federico.milano@ucd.ie

***Abstract*—The focus of this paper is to determine whether the penetration of non-synchronous generation and the magnitude of system frequency fluctuations show any statistical correlation. The study is performed using measurement data taken along four years, from 2014 to 2017. Frequency data have been recorded in the authors' lab with a Frequency Disturbance Recorder, whereas archival wind generation data have been provided by EirGrid Group, the Irish transmission system operator. The all-island Irish transmission system appears to be particularly appropriate for this kind of studies as non-synchronous generation, mostly from wind power plants, can supply to 65% of the instantaneous demand. Results show that the standard deviation of the frequency of the grid is highly correlated to the share of wind penetration.**

***Index Terms*—Non-synchronous generation, grid frequency, wind generation, correlation, frequency disturbance recorder.**

I. Introduction

A. Motivation

The power generated by wind and photovoltaic power plants, often referred to as Variable Renewable Generation (VRG), is affected by uncertainty and volatility. Moreover, VRG, unlike conventional generation, is connected to the grid through power electronic converters and is thus "non-synchronous", i.e., does not respond to grid power unbalances by varying its frequency. For this reason, the high penetration of VRG makes frequency control more complex as fewer synchronous generators are available to provide the system with inertia and power reserve.

The penetration of VRG is expected to consistently increase in the future. For example, the Irish government has set a target to achieve 40% consumption of electricity from renewable energy resources by 2020 [1]. This is a significant step with respect to the current situation. In 2017, in fact, 26.4% of the electricity demand of the all-island Irish transmission system (AIITS) was supplied by wind power [1].

The reduction of conventional generation and, thus, of the total inertia available in the system, as well as the increase of uncertainty and volatility due to VRG can lead to systems with potentially high frequency deviations, which, in turn, can lead to higher risks of instability. With this regard, this paper focuses on the impact of wind penetration on the frequency fluctuations in the grid based on historical data. The goal is to quantify the statistical correlation between wind generation and frequency standard deviation.

B. Literature Review

Several studies have been carried out to define the minimum level of the percent share of instantaneous demand to be supplied by synchronous generators and ensure a proper inertial response of the system. In [2], the impact of high penetration of VRG on the frequency stability in continental Europe is analyzed. The obvious need for balancing services in continental European power systems with high penetration of VRG is stated in [3]. In [4], the impact of higher penetration of VRG on the frequency stability of the US Eastern Interconnection is discussed. A study on the Spanish grid carried out in [5], considers the rate of change of frequency (RoCoF) to calculate the limit of maximum penetration for wind energy in the grid. Given a certain power unbalance, in fact, the RoCoF can be used as an indirect measure of the total inertia present in the system.

The capacity of an electrical grid has a great impact on the definition of a maximum penetration of VRG. The size of continental European network makes it more robust as far as system frequency dynamics are concerned [2]. On the other hand, isolated systems, such as the AIITS, are potentially more fragile from the dynamic point of view [6]. A study based on simulation analyzes the impact of high VRG, in isolated electrical power system, on frequency stability and system security [7]. Another study attempts to determine, with a simplistic qualitative approach, the impact of various types of wind turbines on the frequency control in the AIITS [8]. The maximum penetration of non-synchronous generation and minimum inertia requirements in the AIITS based on simulation results is discussed in [9].

The most critical periods for frequency control are the periods with high VRG output and low demand. This means fewer synchronous generators are available to fulfill the system inertia requirements. Such periods have a significant effect on frequency dynamics and thus on power system security [5]. In Ireland, the DS3 project (Delivering a Secure Sustainable Electricity System) is aimed at increasing the level of penetration of non-synchronous generation (SNSP) up to 75% [10]. So far, the DS3 project has demonstrated that providing system-wide synthetic inertia can be a solution to alleviate high RoCoF rates [11].

The aforementioned studies consider software simulation and predetermined scenarios. A different approach, based on actual measurements, is used in [12] to determine the correlation between non-synchronous generation and RoCoF for the German and Austrian grids. This paper makes a similar study as in [12] but considers the standard deviation of the system frequency instead of RoCoF.

C. Data Acquisition

TSOs generally keep a record of the power generation along the years but very rarely frequency measurements obtained with PMUs or other instrumentation are stored for a long time. Typically, only major events that lead to high frequency deviations are recorded. For this reason, the AMPSAS project, carried out at University College Dublin has recorded the frequency within the university campus in Belfield for a period of four years, from 2014 to 2017. The measurements were obtained with a Frequency Disturbance Recorder (FDR) that has been lent to the last author by the Power system Group led by Prof. Yilu Liu, University of Tennessee, Knoxville [13].

The FDR is a FNET/GridEye device, developed at Virginia Tech, that measures the frequency, phase angle and voltage of the power signal found at ordinary electrical outlets. The main goal of the FNET project is to register and analyze frequency variations following large disturbances [14], [15]. One of the goals of the AMPSAS project, on the contrary, is to explore the statistical properties of the frequency over a long period. Preliminary results of these studies have been presented in [16] and [17].

D. Contributions

This paper studies the impact of wind penetration on the system frequency stability within the AIITS. The main contribution is a statistical analysis of frequency measurements as well as wind generation data for four years, namely from 2014 to 2017. Wind data have been provided by EirGrid Group, the Irish TSO.

Specific contributions are as follows:

- Quantify with proper statistical indices the correlation between the wind penetration and frequency fluctuations. These are Pearson's correlation coefficient and the p-value.
- Understand whether the increasing penetration of wind generation in the Irish system in the past four years has led to increase the volatility of the frequency.

E. Organization

The remainder of the paper is organized as follows. Section II discusses the assumptions made for the analysis whereas Section III provides the rationale for the use of Pearson's correlation coefficient and the p-value. Section IV presents the results obtained from the statistical analysis of the data. Finally, in Section V, conclusions and future work directions are drawn.

II. Background on Wind Generation in the AIITS

Wind speed variations include *uncertainty* (variation with respect to a forecast average value in a given time period) and *volatility* (fast variations around the average value). Volatility is a low amplitude noise that averages out if the number of wind power plants is high. Volatility has thus a small impact on frequency deviations and, ultimately, cannot be distinguished from load variations and other noises present in the grid. The analysis carried out in this paper focuses exclusively on the impact of the uncertainty of wind generation.

Another important aspect that has to be taken into account is the fact that, in the Irish system, wind generation is often not fully dispatched (this operation is called *wind dispatch down*) $P_{\rm WD}$:

$$P_{\rm WD} = P_{\rm wind-avail} - P_{\rm wind-gen} \ , \tag{1}$$

where $P_{\rm wind-gen}$ is the actual wind power generation and $P_{\rm wind-avail}$ is the total power available from the wind. If $P_{\rm WD} > 0$, there is a wind power reserve and thus the stochastic variations of the wind do not affect the power unbalance of the network, and are consequently not responsible of frequency variations.

Finally, to properly decide the correlation between wind generation forecast and frequency deviations, some precautions have to be taken into account. In particular, we have to exclude from the analysis the periods during which the load demand varies significantly (known as *demand ramping*). The variation of the load, in fact, leads to generator rescheduling that causes fast variations of the frequency. These variations are clearly independent from the wind generation.

The remainder of this section outlines the wind dispatch-down procedure and demand ramping up and down as defined in the network codes of the AIITS.

A. Wind Dispatch-Down

Wind dispatch-down refers to the available wind energy that is not allowed in the grid. This dispatch-down of wind is affected by both local network constraints and system-wide security issues and is necessary to ensure the safe and secure operation of the grid. Wind farms receive dispatch-down instructions from EirGrid [18]. This instructed dispatch is subject to curtailments and constraints [18]. To determine the dispatch-down volume required by the wind farms, EirGrid solves the power flow problem with all required constraints in place one hour before the dispatch instructions with the updated forecast of the available wind energy. Table I shows the volume of monthly wind dispatch-down as percentage of the total available wind energy per year under study [1].

The technical procedures and constraints implemented by EirGrid are outlined below.

1) Curtailments: Curtailments refers to the dispatch-down of wind due to the limits imposed by the power system [1].

(a) *System Non-Synchronous Penetration Limit.* The system non-synchronous penetration limit (SNSP) is defined as:

$$\text{SNSP} = \frac{\text{Wind Gen} + \text{HVDC Imports}}{\text{System Demand} + \text{HVDC Exports}} \cdot 100 \ , \tag{2}$$

and is used by EirGrid for ensuring a secure and sustainable operation of the grid i.e., the grid frequency does not

TABLE I: Wind dispatch-down as percentage of total available wind energy per year for the Irish system in the period from 2014 to 2017.

Year	2014	2015	2016	2017
Jan	–	4.3	3.5	–
Feb	–	4.2	3.1	1.7
Mar	–	8.8	–	3.3
Apr	–	2.0	1.3	3.6
May	–	4.3	1.2	3.5
Jun	–	4.8	–	4.1
Jul	3.4	3.7	–	3.2
Aug	3.6	5.6	–	2.9
Sep	1.8	2.5	–	5.1
Oct	–	3.9	1.8	10.6
Nov	–	–	1.3	2.6
Dec	4.9	6.3	3.3	–

deviate much due to SNSP penetration [19]. The SNSP is calculated for each trading period using (2) [19]. The HVDC imports and exports of electricity in (2) come from Moyle and East-West HVDC inter-connector with the Great British grid. There has been an increment of 5% per year in the SNSP limit starting from 50% in 2014 to 65% by the end of 2017 [20]. SNSP limit is imposed by system demand. This means the AIITS can accommodate more wind if demand levels are high as it happens during the day from 10:00 to 20:00 when demand is generally high. Wind curtailment will be higher in the case of low demand with high wind production.

(b) *Rate of Change of Frequency (RoCoF)/Inertia.* The system frequency is an indirect measurement of the balance between supply and demand. If a contingency involving the outage of a generator or the loss of load occurs, the frequency deviates from the reference frequency under balanced operation, e.g., 50 Hz in Europe. The rate with which the frequency deviates away from the mean is known as the rate of change of frequency (RoCoF) [1]. An event causing high RoCoF rates can drive the system towards instability. EirGrid must ensure a minimum number of synchronous generators to be online in different locations of the power system to provide inertia to avoid higher RoCoF and hence, maintain system stability. For this reason, EirGrid may ask the wind farms to dispatch down in order to maintain the power system balanced and provide inertia to avoid high RoCoF rates. Note, however, that only a negligible volume of available wind energy was curtailed, during the period under study in this paper, due to RoCoF/inertia [1].

(c) *Operating Reserve Requirements.* TSOs must ensure a certain amount of operating reserve to be available in the power system to provide for the imbalance occurred due to the greater variations of system demand. This reserve cannot be provided from non-synchronous wind penetration. Hence wind production has to be dispatched down to provide room for operating reserve. In the AIITS, wind curtailments are generally higher overnight, i.e., from 23:00 to 09:00 [1].

2) Constraints: The dispatch-down of wind due to technical constraints imposed by the network are known as constraints. Firstly, constraints can be understood as localized power carrying capacity of the network at the region of wind production. Secondly, outages in the network that may occur due to maintenance, upgrade works or faults. The dispatch-down of wind in the AIITS remains almost the same throughout the day irrespective of demand levels [1].

B. Demand Ramps

Figure 1 shows the load profile of the AIITS during a typical day, for different months. Conventionally, the period from 10:00 to 16:00 is called *day hours* and the period from 16:00 to 10:00 *night hours*. The system demand generally ramps down between 18:00 and 04:00. Then system demand ramps up from 04:00 to 10:00 and from 16:00 to 18:00 hours. Load ramping leads to greater variations of the grid frequency during night hours. As discussed above, to be able to identify the impact of wind generation on the system, the effect of load ramping has to be separated as much as possible from the frequency deviations. In the case study, thus, only day hours are considered.

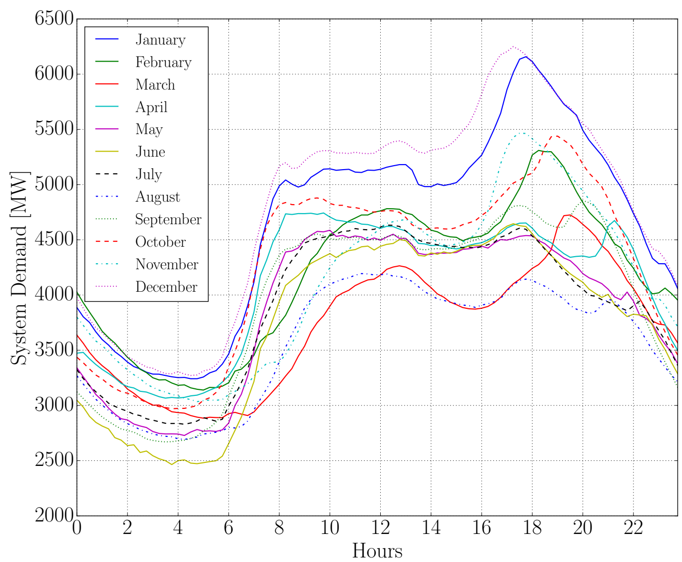

Fig. 1: System Demand for a particular day for all the months in 2016.

III. Correlation Indices

We consider two statistical indices to evaluate the correlation between wind generation and frequency deviations, namely, the Pearson's correlation coefficient and the p-value.

A. Pearson's correlation coefficient

The Pearson's correlation coefficient is a measurement of the linear correlation between two variables [21], as follows:

$$r = \frac{\sum_i^N (X_i - \overline{X})(Y_i - \overline{Y})}{(N-1)\sigma_X \sigma_Y} \ , \tag{3}$$

where N is the number of observations; X_i and Y_i are the values of the two time series, with length N, whose correlation is to be calculated; $\overline{X}$ and $\overline{Y}$ are the mean values of the time series X_i and Y_i, respectively; and σ_X and σ_Y are the standard deviations of the time series X_i and Y_i, respectively.

The Pearson's correlation coefficient can take any value between -1 and 1. $r = 1$ and $r = -1$ indicate perfect linear relation between the variables, whereas $r = 0$ indicates a non-linear relation. In particular, $r > 0$ indicates that if X increases also Y increases. Only positive correlation coefficients are observed in the case study discussed in this paper.

B. *p-value*

The Pearson's correlation coefficient reflects the degree of correlation between two variables but does not provide any information weather such a correlation is significant or not. The index used to express the statistical significance of a correlation is known as p-value [22].

Given the t-distribution:

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}} \ , \quad (4)$$

the p-value is defined as:

$$p\text{-value} = 2\Pr(T > t) \ , \quad (5)$$

where T follows a t distribution with $N-2$ degrees of freedom. Hence the p-value is twice the probability (for double tail events) to obtain the current value of r if the correlation were actually zero (*null hypothesis*). The null hypothesis for this study is defined as the lack of correlation between wind generation and the hourly standard deviation of the frequency.

Being a probability, the p-value range is $[0, 1]$. A small p-value implies the rejection of the null hypothesis and imposes that the correlation r is significant. The conventional threshold $p = 0.05$ is chosen in the case study to validate statistical significance of a correlation between the variables [22]. So, if $p < 0.05$, we assume that frequency fluctuations are statistically correlated with the penetration of wind generation in the system.

IV. Case Study

As anticipated in the introduction, two sets of data are considered in this case study, as follows.

(a) *Wind Generation Data.* These data were provided to the authors by EirGrid Group, for the same period of four years (2014-2017). The data-set acquired consists of instantaneous power in MW for wind production, system demand and total generation in 15-minute time series records. These values have been averaged using minutely measurements over a period of 15 minutes from the SCADA system of the AIITS.

(b) *Frequency Data.* These data for frequency have been collected at the AMPSAS project Laboratory using a FDR. The measured frequency data has been stored as time series records. Each measured value represents grid frequency every 0.1 second. This data is available starting from July 2014 to November 2017.

TABLE II: Pearson's coefficients for $P_{\text{wind}\%}$ and σ_{f} for the Irish system in the period from 2014 to 2017.

Year	2014	2015	2016	2017
Jan	–	0.2400	0.4939	–
Feb	–	0.5919	0.4233	0.4595
Mar	–	0.3923	–	0.3599
Apr	–	0.4756	0.2075	0.4971
May	–	0.5009	0.4127	0.5374
Jun	–	0.4198	–	0.1424
Jul	0.3692	0.5791	–	0.3987
Aug	0.5033	0.5514	–	0.4029
Sep	0.4513	0.3615	–	0.3063
Oct	–	0.5759	0.5793	0.3580
Nov	–	–	0.5997	0.4053
Dec	0.4619	0.3660	0.3374	–

The Pearson's correlation coefficients and p-values are calculated taking $X = P_{\text{wind}\%}$, i.e., the instantaneous value (15-minute values averaged over 1 hour) of wind energy produced in an hour as percentage share of system demand:

$$P_{\text{wind}\%} = \frac{\text{Hourly Averaged Wind Production}}{\text{Hourly Averaged System Demand}} \cdot 100 \ , \quad (6)$$

and $Y = \sigma_{\text{f}}$, i.e., the standard deviation of the system frequency over the same period for which $P_{\text{wind}\%}$ is calculated.

Table II shows the correlation of $P_{\text{wind}\%}$ with σ_{f} per month in the period from 2014 to 2017. Note that frequency data were not available for some months. The wind penetration and frequency fluctuation show a relatively large correlation ($r > 0.4$) in most of the months.

Table III shows the p-values for the same months considered in Table II. All value are well below 0.01 except for three months (January 2015, April 2016 and June 2017), which, consistently, are the same months that show the lowest values of the Pearson's correlation coefficients. Interestingly, these three months are all in different years.

TABLE III: p-values for $P_{\text{wind}\%}$ and σ_{f} for the Irish system in the period from 2014 to 2017.

Year	2014	2015	2016	2017
Jan	–	$1.51 \cdot 10^{-2}$	$< 10^{-6}$	–
Feb	–	$< 10^{-6}$	$6.80 \cdot 10^{-6}$	$< 10^{-6}$
Mar	–	$1.21 \cdot 10^{-7}$	–	$5.84 \cdot 10^{-5}$
Apr	–	$< 10^{-6}$	$1.92 \cdot 10^{-2}$	$< 10^{-6}$
May	–	$< 10^{-6}$	$5.84 \cdot 10^{-5}$	$< 10^{-6}$
Jun	–	$< 10^{-6}$	–	$9.55 \cdot 10^{-2}$
Jul	$9.82 \cdot 10^{-5}$	$< 10^{-6}$	–	$3.44 \cdot 10^{-6}$
Aug	$< 10^{-6}$	$< 10^{-6}$	–	$< 10^{-6}$
Sep	$4.15 \cdot 10^{-7}$	$1.33 \cdot 10^{-5}$	–	$1.31 \cdot 10^{-4}$
Oct	–	$< 10^{-6}$	$< 10^{-6}$	$3.36 \cdot 10^{-6}$
Nov	–	–	$< 10^{-6}$	$7.71 \cdot 10^{-6}$
Dec	$< 10^{-6}$	$6.97 \cdot 10^{-6}$	$4.65 \cdot 10^{-5}$	–

The least correlated month is June 2017, while the maximum correlated month is November 2016. Figures 2 and 3

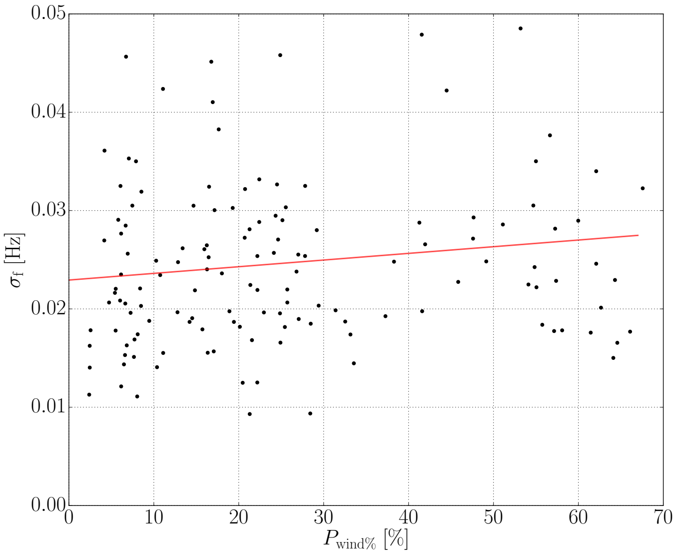

Fig. 2: Scatter plot of σ_f vs $P_{\text{wind\%}}$ for the month of June 2017.

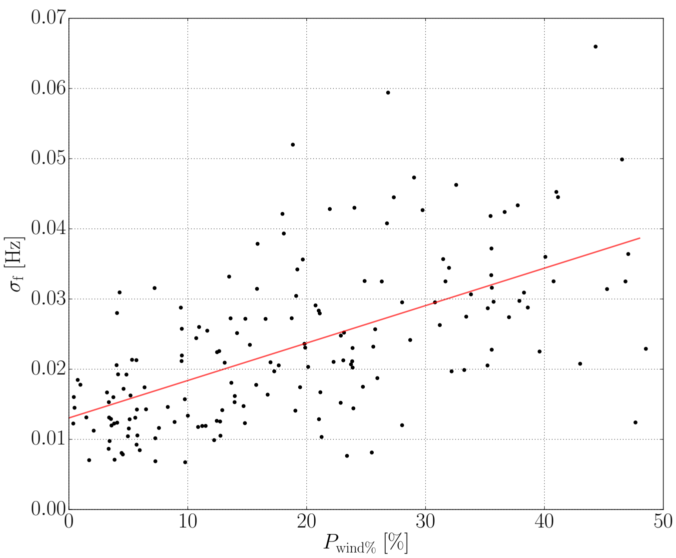

Fig. 3: Scatter plot of σ_f vs $P_{\text{wind\%}}$ for the month of November 2016.

present the scatter plot where x-axis represents $P_{\text{wind\%}}$ and y-axis is σ_f for the months of June 2017 and November 2016, respectively. In June 2017, the wind penetration has been greater than 50% for a significant number of hours, whereas, in November 2016, the wind penetration remained below 50% all time. Still wind penetration and frequency fluctuations are more correlated in November 2016 than in June 2017. Moreover, in June 2017, there are several hours with a high standard deviation of the frequency but these hours are mostly characterized by low value of $P_{\text{wind\%}}$. In November 2016, the hours with higher σ_f are mostly characterized by high $P_{\text{wind\%}}$.

These apparently mixed results can be explained by comparing the values of P_{WD} in different periods. Figure 4 shows the histogram of P_{WD} for four relevant months, where x-axis represents P_{WD} and y-axis shows the number of hours

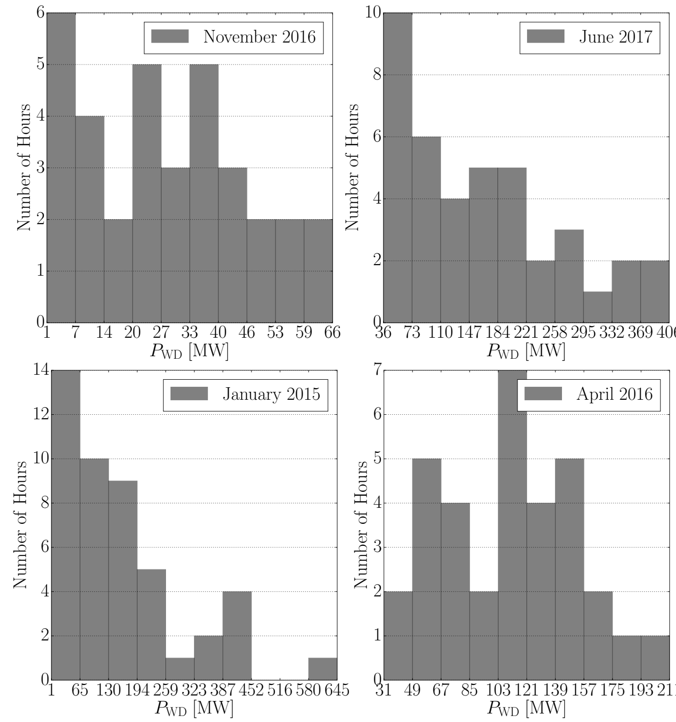

Fig. 4: Histogram of P_{WD} for the months of November 2016, June 2017, January 2015 and April 2016.

for which the wind dispatch-down happend. Comparing the histograms and looking at the values in Table II, it is evident that the month with greater number of hours during which P_{WD} is high shows a relatively low correlation between wind generation and frequency variations. This supports the argument made in Section II that the higher the amount of wind rejected, the lower the correlation in a given month.

April 2016 is an excetion to this rule. This month shows a low correlation between wind and frequency variations despite having a lower P_{WD} and fewer hours of wind curtailment, compared to January 2015. However, we note that, in 2016, the AIITS faced a significant number of the transmission outages, mainly due to maintenance and refurbishment of the transmission system [1]. These outages led to significant changes in the transmission network topology, which could be the cause for such a low correlation in the month of April 2016.

V. Concluding Remarks and Future Work

This work explores the correlation between wind penetration in the AIITS and standard deviation of the system frequency. Time stamped data for four years, between 2014 and 2017, for wind penetration and a high resolution data for grid frequency measured at AMPSAS Laboratory was used in this study. We can conclude that a statistically significant correlation exists between wind penetration and frequency deviations.

Load variations have a strong impact on frequency fluctuations and thus, the correlation between wind and frequency can be observed only if the load demand does not vary too much.

As explained in Section II, forecast error is not the cause of the frequency variations in the AIITS because wind is subject to curtailments. The results of the statistical correlation analysis confirm that if in the month the wind dispatch-down is high for long periods, the correlation between wind generation and frequency variations is relatively low.

These results support the argument that wind production is no longer a stochastic variable of the system if subjected to curtailments and hence the wind penetration is not crucial, as one would expect, for the fluctuation of the frequency. It is rather the non-synchronous nature of wind generation that determines the quality of the system dynamic behavior.

A limitation of the study carried out in this paper is that available wind generation data have a resolution of only 4 values per hour. On the other hand, frequency data obtained with the FDR have a resolution of 10 values per second. It appears desirable to obtain a higher resolution data for instantaneous wind penetration. This will help to perform a multivariate correlation analysis that includes the information of standard deviation of instantaneous penetration of the wind in the network. Further information about the ramp rates of the instantaneous wind penetration can be included. A higher resolution of wind data can allow developing a precise regression model which can be utilized for model predictive control.

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