Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Protections Impact on the Availability of a Wind Power Plant Operating in Real Conditions

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Abstract **– This paper addresses a number of aspects referred to availability of the wind turbines operating in a wind power plant. Starting from the experimental data gathered on-site through SCADA systems, and from a recorded data indicating the operation of various types of protections, the causes of unavailability are investigated in terms of determining the impact of the different types of failures as represented by the tripping of the corresponding protections. The results obtained show that the variability of occurrence and duration of the protection tripping for the different wind turbines is relatively high. This impacts on the identification of suitable values and shapes of the failure parameters that can be used to build a reliability model of the wind power plant with probabilistic entries. For this purpose, some indications for constructing a probabilistic model of the protection operation are provided, also taking into account the possible simultaneous tripping of the protections due to mutually dependent events.**

Index Terms **– availability, protection system, reliability, wind power plant, wind turbines.**

I. Nomenclature

A. General acronyms

DFIG	Doubly Fed Induction Generator
FOF	Forced Outage Factor
FOH	Forced Outage Hours
FOR	Forced Outage Rate
PDF	Probability Density Function
PH	Period Hours
TH	Total Hours
WT	Wind Turbine

B. Protection code acronyms

BIL	Blade Ice Limit
FOL	Frequency Outside Limits
GOL	Gearbox Oil Level
GTT	Gearbox/Transformer Temperature Limit
MCV	Minimum Controller Voltage
MGS	Maximum Generator Speed
MWS	Maximum Wind Speed
ROC	Rotor Overcurrent
RRE	Rotor Relay Configuration Error
SOC	Stator Overcurrent
SRE	Stator Relay Configuration Error
VOL	Voltage Outside Limits

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978-1-4244-2235-7/09/$25.00 ©2009 IEEE

II. Introduction

In the last decades, the energy production from renewable energy sources has significantly increased, especially in some countries in which specific energy policies have provided incentives to encourage the generation from these sources instead of conventional ones. Wind power technology is the main renewable energy entrant on the electricity generation sector, being the only competitive substitute to the classical power plants in the large-scale. Incentives from energy authorities, cost reductions and technological efficiency enhancement are making wind power systems able to reach an extraordinary growth worldwide. Only in the EU, the new installed capacity in wind power systems increased in 2008 by 15% [1]. The large diffusion of wind plants has significant impacts on the electrical system, including planning, operation and power quality aspects [2-4]. Various features refer to the impact of wind generation onto reliability issues [5-10]. To focus on these aspects, a detailed analysis of wind power plant availability in real cases is particularly helpful [11].

This paper deals with experimental assessment of the data obtained from SCADA systems installed on the wind turbines (WTs) of a 27-MW wind power plant. A first part of the assessment is based on the data obtained from monitoring the wind system over a period of about six months. The data provided by SCADA systems are the 10-min parameters of active power and the wind speed of each turbine. A comprehensive analysis based on the measurements has been carried out to determine the WT availability according to a set of relevant indicators [5].

A further part of the assessment is dedicated to the detailed study of the protection system effects on WT availability. In this case, the data used refer to a specified period of operation (from 1 to 14 months, depending on the WT), during which the occurrence and duration of the protection tripping events have been recorded. The following sections contain a comparative analysis of the outcomes obtained from various WTs of equal size, manufacturer and rated parameters, thus providing a contribution to the investigation of some aspects referred to WT reliability and maintenance.

III. Wind System Characteristics

The wind power plant under analysis is located in Italy, on a very irregular terrain, at an altitude of about 1200 m, and consists of 32 WTs, each of them having a rated power equal to 850 kW and using a Doubly Fed Induction Generator (DFIG). The Wind Farm, with total rated power of 27.2 MW, is divided into three wind parks:

both the first and the second wind park include eleven WTs each, while the third one has ten WTs. The whole site is distributed over a length of 7 km. The power plant is connected to the high voltage (HV) distribution network through a 20 kV / 150 kV power substation.

The productivity of the WTs depends on the wind features and on several technical aspects. A specific issue of each WT is the wind speed limit, with a lower wind speed of 4 m/s for WT operation and higher wind speed limit of 25 m/s, beyond which the WT is switched off. Moreover, the wind system production can be affected by the presence of the fault ride-through capability [12], which differs from one transmission operator to another [13,14]. The events with a significant impact onto WT availability analysis are addressed in this paper. According to the Italian standards, the protections required at the grid interface should be installed both at the high voltage side and at the low voltage (LV) side (in our case 690 V), where the DFIGs are connected.

IV. Availability Assessment

Various indicators have been defined in [5] to evaluate specific aspects of the performance of power generation from wind systems. However, the availability approach using these indicators can be assessed considering either a machine or the entire wind plant. A detailed description of the above mentioned indicators is given in [15]. In addition to these availability indicators, the performance of an individual generating unit can be assessed using the Forced Outage Factor (*FOF*), usually applied to high-use machines [16] such as wind generators. Let us consider the time period in which the unit has been in active state, called Period Hour (*PH*), namely, the difference between the total number of hours and the hours in which failure conditions have been detected. Let us further take from [17] the definition of Forced Outage Hours (*FOH*) as the number of hours in which a generating unit reaches at least one of the main unplanned outage conditions. Hence, the *FOF* can be defined as

$$FOF = (FOH / PH) \cdot 100 \quad (1)$$

Furthermore, the performance of wind generators can be expressed by using the Forced Outage Rate (*FOR*), given by the ratio between *FOH* and the total number of hours (*TH*) in which the generator was monitored:

$$FOR = (FOH / TH) \cdot 100 \quad (2)$$

For the wind system analysed, the wind generators have been monitored for a number of hours *TH*.

Fig. 1 shows the results of the *FOF* and *FOR* indices for the various WTs[2], as well as the values of *PH* for the WTs, slightly lower than the corresponding *TH* values. High values of *FOF* and *FOR* occur for WT #10 in wind park #1, WT #29 and WT #32 in wind park #2, as well as WT #18 and WT #24 in wind park #3. Especially in these cases, the protection tripping had a significant impact on the availability of these WTs. As such, comparison between *FOF* and *FOR* of the same WT leads to slightly different results. The assessment results presented here partially differ from the ones shown in [15], in which the periods of low wind speed (less than 4 m/s) were excluded from the analysis.

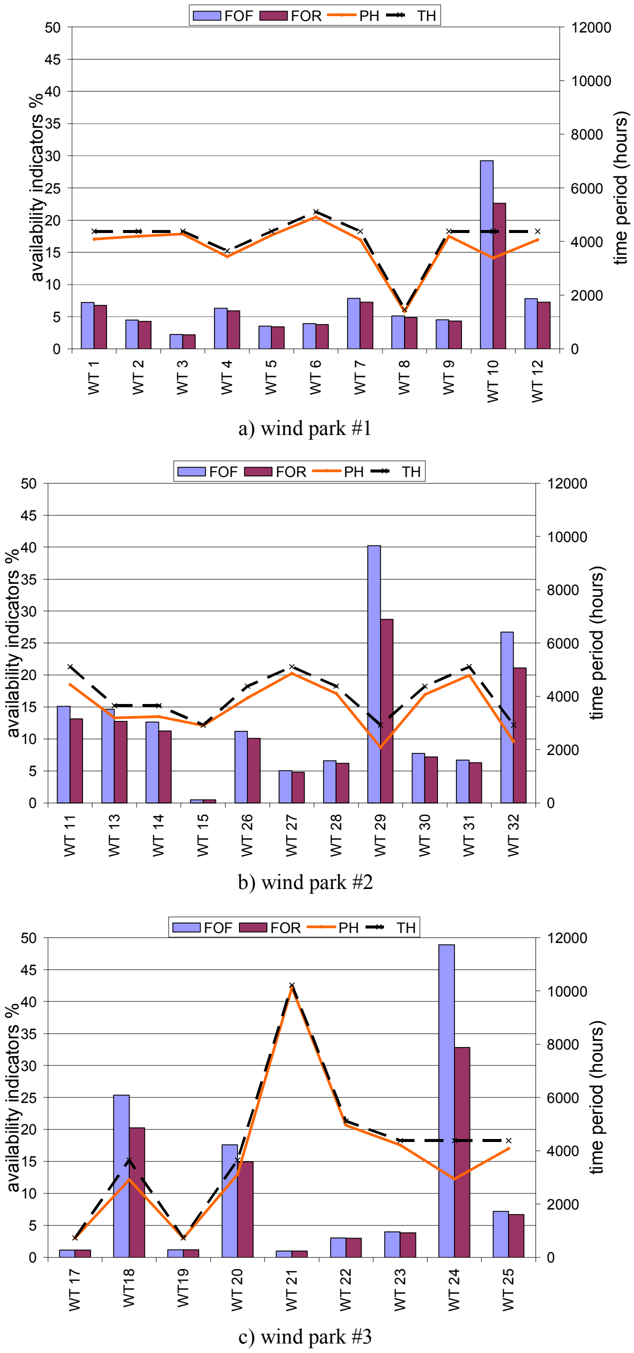


Fig. 1. Availability indicators for the WTs in the three wind parks.

V. Assessment of the Protection System Operation

Availability of the WTs from each wind park is further analysed by taking into account a detailed database which provides information about the protections used and their operation. The information regarding the relay protection system is used to carry out a general survey of specific failures and their effects on WT availability. Furthermore, the frequency of occurrence and duration of protection tripping events for all WTs are further considered in the analysis. The main relay database scheme consists of twelve protections,

[2] The results for WT #16, located in wind park #3, are not indicated due to lack of available data.

usually characterised by specific parameters. The protections are denoted with synthetic acronyms, as indicated in the Nomenclature section, and are assigned the numbers indicated in Table I for representation purposes.

TABLE I
PROTECTION ACRONYMS WITH THEIR ASSIGNED NUMBERS

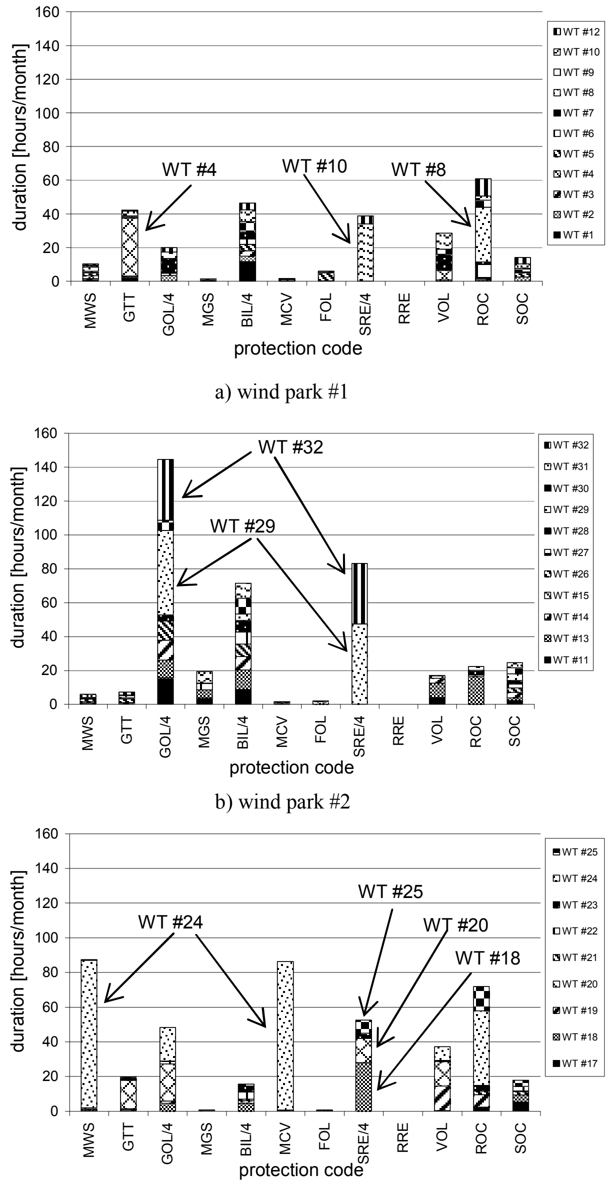
number	*acronym*	*number*	*acronym*	*number*	*Acronym*
1	MWS	5	BIL	9	RRE
2	GTT	6	MCV	10	VOL
3	GOL	7	FOL	11	ROC
4	MGS	8	SRE	12	SOC

A. Duration of the protection tripping

The assessment of the protection tripping duration consists of computing the duration for which the WTs are switched off due to one or more components tripped out by their relays. The tripping process is the time interval characterised by the failure and the lack of productivity of WTs. The determination of the protection tripping duration for the wind system under analysis is easy, since the initial and final instants of tripping are stored in a specific database.

Fig. 2 shows the results of the protection operation for each of the three wind parks. Since the period of monitoring is different for each WT, in order to get comparable results the duration is reported to one equivalent month (30 days) and expressed in hours/month. In addition, for the sake of representation the results shown in Fig. 2 for GOL, BIL and SRE are divided by 4. The longer duration for which the protection system has to deal with failures refers to wind park #2 and to wind park #3.

From Fig. 2, it is clearly evident that the various WTs exhibit significantly different operation of their protection systems, as well as highly different duration of protection tripping. These aspects are critical in order to perform a synthetic availability study. The main problems during WT operation refer to the gearbox oil level (GOL), especially at wind park #2, where in the case of WT #29 the duration of protection tripping reaches almost 200 hours/month, and for WT #32 around 145 hours/month. Other events regarding the duration of the protection tripping are assigned to the ice on the WTs blades (BIL) and to the error which emerges at the stator relay configuration (SRE). As in the first case, the highest value of the duration of BIL protection has been recorded at wind park #2, but is extended in a uniform way at all WTs from this wind park. Moreover, in the case of the SRE protection, high values of protection duration have been found at WT #10 from wind park #1, WT #29 and WT #32 from wind park #2, as well as WT #18, WT #20 and WT #25 from wind park #3.



a) wind park #1

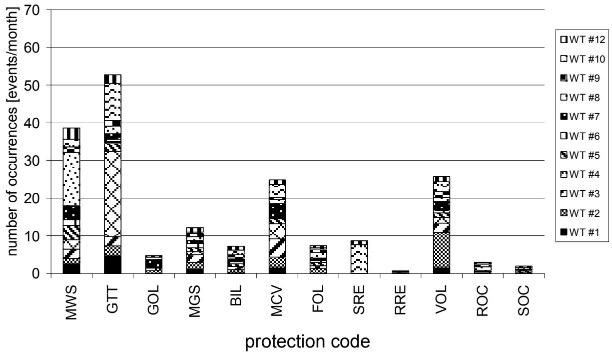
b) wind park #2

c) wind park #3

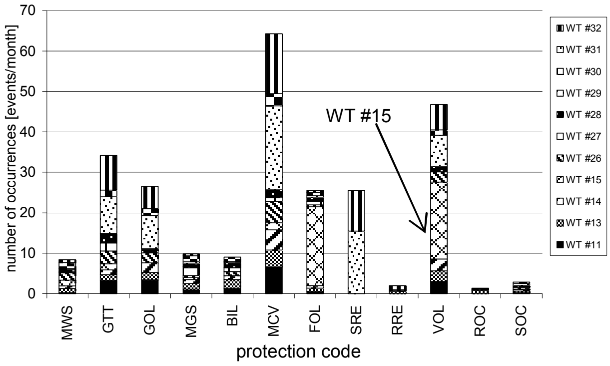
Fig. 2. Lack of operation duration for the WT protections.

B. Frequency of the WTs failures

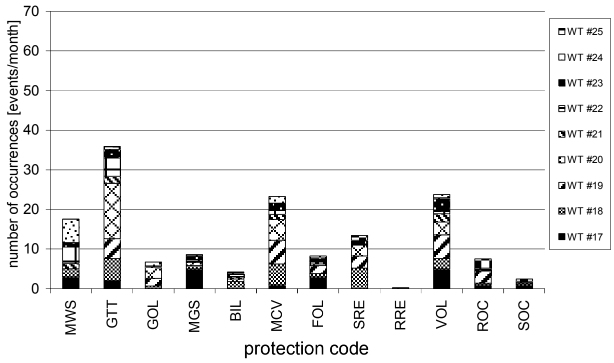
Fig. 3 shows the frequency of the failures for each wind park. The number of occurrences is reported in events per month, in order to make the recorded data (referred to different recording periods) comparable. These results come to sustain the study of the protection schemes impact on the availability of wind generators. Again, the number of protection occurrences emphasises the diversity of WT behaviour, even though the machines have the same rated parameters, are equal in size and are built by the same manufacturer. For reliability studies, the evaluation of the number of occurrences is typically complementary with respect to the duration of protection tripping. For instance, although the duration of the GOL, BIL and SRE protection tripping is relatively high, the corresponding frequency of protection tripping is quite low. Instead, the maximum wind speed (MWS) protection, the activation of temperature limit of the gearbox (GTT), minimum controller voltage (MCV) and voltage limits (VOL) protections appear with a significantly high proportion, but their incidence on duration is rather low. The superior limit of the wind speed ($w > 25$ m/s) is exceeded in particular at wind park #1 with about 40 events/month, and at wind park #3 with almost 20 events/month. The different values of wind speed between the wind parks, and consequently between each machine, mainly depend on the irregularity of the land where the wind generators are installed. Moreover, sometimes the voltage goes beyond its limits, especially at WT #15 in wind park #2.



a) wind park #1



b) wind park #2



c) wind park #3

Fig. 3. Number of tripping occurrences for the WT protections.

C. *WT reliability components*

The outcomes of the analysis concerning the wind power plant components are helpful to provide an overview of the WT equipment reliability. The wind plant operator can use the information coming from this study to schedule the maintenance of the machines. At the same time, the wind plant operator can establish a well-argued planning analysis of the wind plant productivity based on WT availability.

Fig. 4 outlines the failure frequency of the main WTs components. The most unreliable component is the gearbox system (GOL + GTT), with almost 27% of the failures. Then, the minimum voltage relay has tripped out the wind generators in 18.85% of the cases, while the voltage is recorded outside the limits in 16.15% of the cases. The MCV relay is used to disconnect the WT from the electrical grid when the voltage decreases under an established threshold, in general 85% of the rated voltage [18]. Furthermore, the wind speed behaviour reported at the entire wind plant also emphasises the tripping of the WTs, when the wind speed is beyond its upper limit. A relatively high percentage (namely, 10.85%) is assigned to MWS protection. Problems also occur with the stators and the rotors of the machines.

Even though the frequency at which the VOL, MCV and MWS protections trip is relatively high, the duration for which these protections trip out the generators is relatively low. Instead, according to Fig. 5, the gearbox systems (GOL + GTT) overtake 34% of the tripping failure duration process, confirming again that this component is a major issue reflected onto the availability of the wind plant.

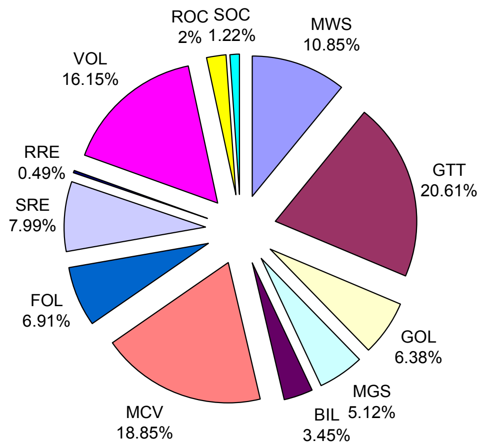


Fig. 4. Overview of the number of tripping occurrences for the WT protections.

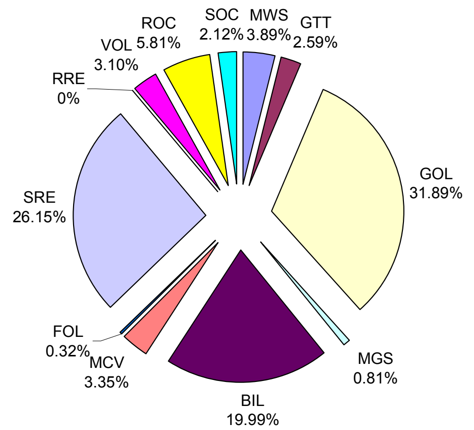


Fig. 5. Overview of the protection tripping duration for the WT protections.

Moreover, poor reliability of the relay which controls the errors arisen in the stator is demonstrated by almost 26% of the total protections duration. Another WT part with impressive tripping time is the blade system. In this case, the duration of the BIL protection is 20%. Indeed, in the wind plant under analysis the ice settled down on the blades occurs quite often due to the altitude where this plant is located.

Fig. 6 shows the probability density function of the protection tripping frequency. Because the data of the protection tripping varies from one WT to another, the time period of analysis is referred to the same baseline time of one month. The number of protection tripping occurrences in this period is relatively low. Fig. 7 presents the probability density function of the protection tripping duration, emphasising that for GOL, BIL, SRE and ROC protections the time of switching off the WTs is widely distributed between the machines and is very high. The PDF shapes are relatively far from those of common probability distributions. On the one hand, there are cases with no protection tripping during the period of event recording, contributing to the presence of a Dirac pulse in the origin. On the other hand, the number of recorded events is relatively low, leading to the dispersed shape of some PDFs shown in Fig. 7. This dispersion could be reduced by defining the duration classes in a different way, but in this case the representation has been left as it stands to remark the low number of data from which it has been originated. Recordings of the protection operation for longer time periods would be needed in order to improve the shape of the PDF representations.

For reliability studies, it is also crucial to address the possible presence of simultaneous or mutually dependent events. For this purpose, the time-sequence of the protections tripping for each wind park is presented in Fig. 8. For the sake of simplicity of the graphic representation, each analysed protection is assigned the number indicated in Table I. Since the duration of each protection tripping is significantly lower than the period of observation, it is not possible to recognise possible simultaneous protection tripping by visual inspection. A comparison between the time interval in which the tripping of a couple of protections can occur at the same time has been carried out. Thus, the study takes into account the frequency of occurrence of simultaneous protection tripping, obtained by summing up the number

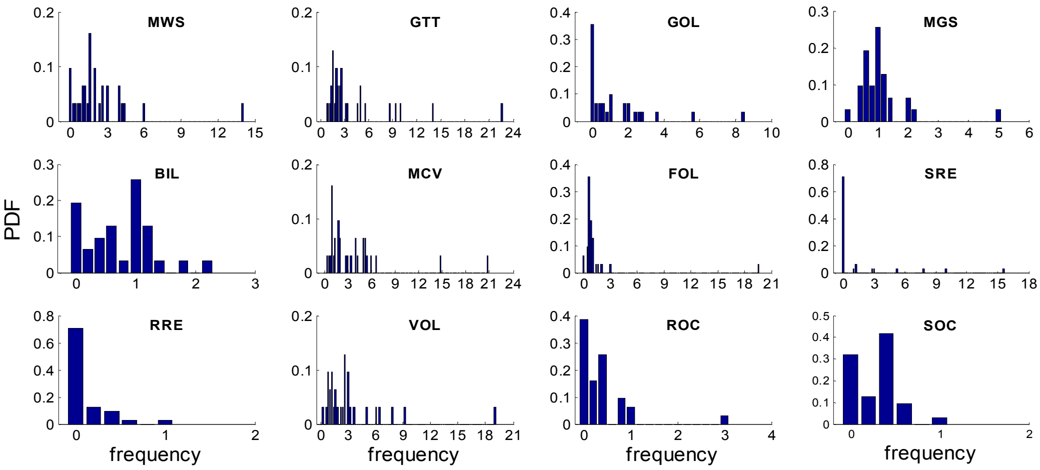


Fig. 6. PDFs of the monthly protection tripping frequency.

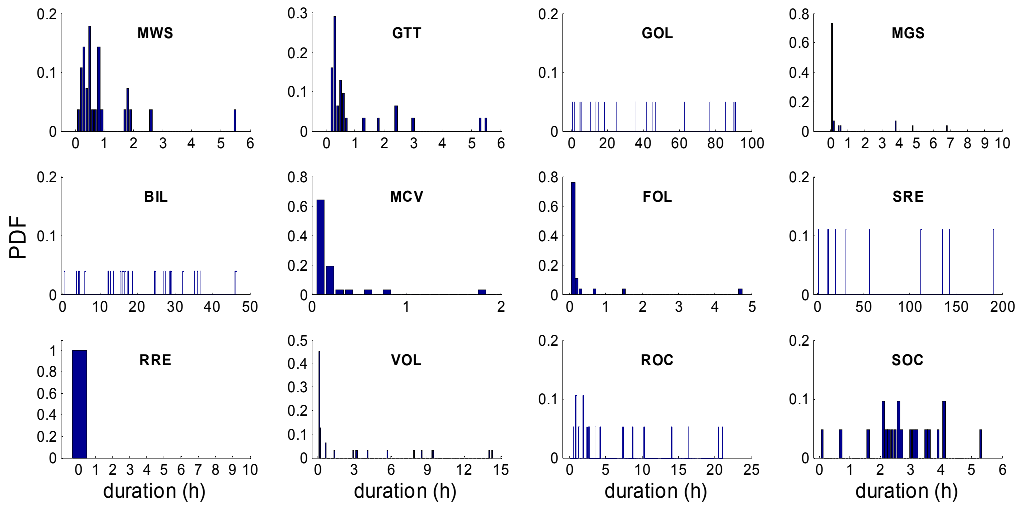
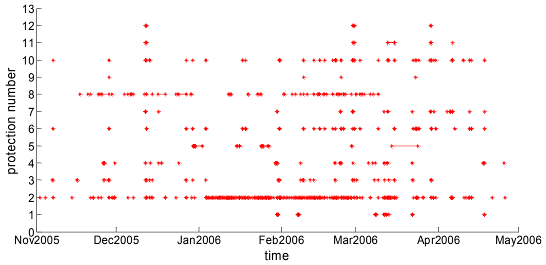
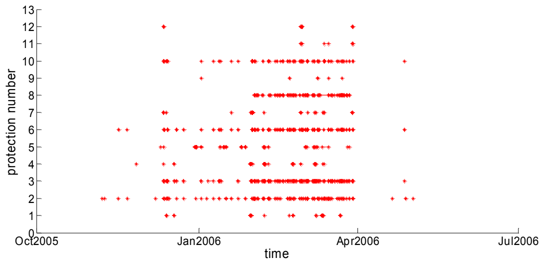


Fig. 7. PDFs of the monthly protection tripping duration.

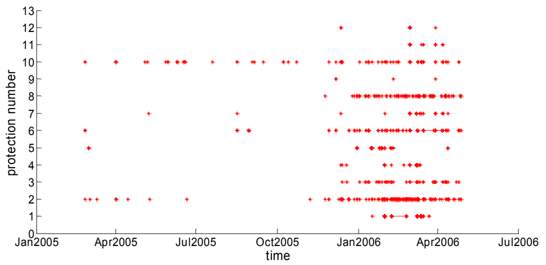
of separate time intervals in which two protections have been activated simultaneously. For the sake of comparability, the results are reported to annual values.



a) wind park #1



b) wind park #2



c) wind park #3

Fig. 8. The time-sequence simultaneity between protections tripping.

Let us denote the set $\tau_k^{(j)}$ of the time periods in which the protection $j = 1,\ldots J$ switches WT #k off, for $k = 1,\ldots, K$, where J is the number of protections and K is the number of WTs monitored (in this case, $J = 12$ and $K = 31$). A first analysis refers to considering each individual WT. For WT #k, a $J{\times}J$ matrix $\hat{\mathbf{C}}_k$ is built, whose generic entry $\hat{c}_k^{(i,q)}$ contains the number of common periods of protection tripping for the protections i and q, evaluated by searching for the intersections between the set $\tau_k^{(i)}$ and the set $\tau_k^{(q)}$. Considering the duration T_k of data recording for WT #k, the matrix $\mathbf{C}_k$ of simultaneous protection tripping reported to one year is obtained as

$$\mathbf{C}_k = \hat{\mathbf{C}}_k \, Y / T_k \qquad (3)$$

where Y is the number of hours in one year.

Fig. 9 presents the results of the aforesaid calculations for WT #10 (that is, the matrix $\mathbf{C}_{10}$). Significant time-sequence simultaneity is shown between MCV, SRE and VOL protections, when the machines are tripped out due to voltage problems.

Furthermore, the protection analysis is extended to calculate the annual frequency of simultaneous protection tripping for a given protection j and for the entire set of WTs. In this case, for a given protection j, the $K{\times}K$ matrix $\hat{\mathbf{\Phi}}_j$ is built according to the same concepts used to obtain the matrix $\hat{\mathbf{C}}_k$. Now, the time-sequence comparison is carried out between WT #m and WT #z. Thus, the generic entry $\hat{\varphi}_j^{(m,z)}$ contains the number of common periods of protection j tripping for WT #m and WT #z, evaluated by searching for the intersections between the set $\tau_m^{(j)}$ and the set $\tau_z^{(j)}$. The results could highlight the occurrence of events at the system level, affecting more WTs at the same time.

In order to report the matrix $\hat{\mathbf{\Phi}}_j$ of simultaneous protection tripping to one year, it is necessary to calculate, for each pair of WTs considered, the duration of the common recording time interval. For instance, taking WT #i and WT #q, the common duration is indicated as $T^{(i,q)}$. In this way, it is possible to introduce the matrix $\mathbf{T}$, containing the components $T^{(i,q)}$, for i, $q = 1,\ldots, K$. In particular, the component $T^{(k,k)}$ is equal to T_k appearing in equation (3). Thus, the matrix $\mathbf{\Phi}_j$ of simultaneous protection tripping reported to one year is obtained as

$$\mathbf{\Phi}_j = Y\left(\hat{\mathbf{\Phi}}_j \,\dot{/}\, \mathbf{T}\right) \qquad (4)$$

where the operator $\dot{/}$ denotes the component-by-component ratio applied to the matrix entries.

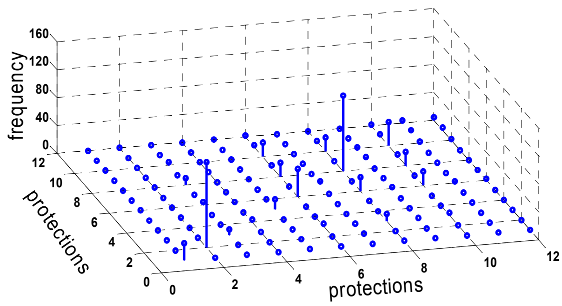
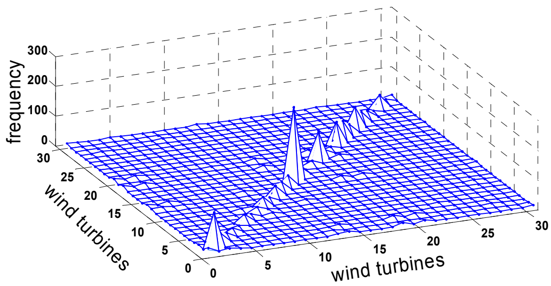
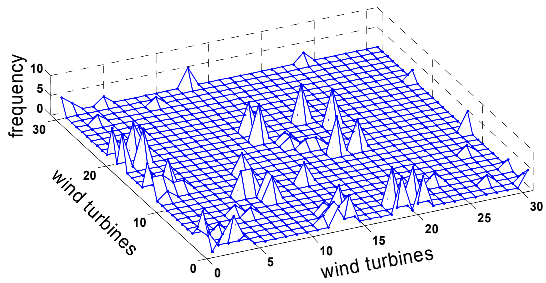


Fig. 9. The frequency of time-sequence simultaneity between protection tripping in the case of WT #10.

Fig. 10a shows the case of VOL protection switching off various WTs in the same time interval. In order to highlight the non-diagonal elements of the matrix, Fig. 10b contains a matrix representation without the diagonal matrix components, from which simultaneous protection tripping emerges for many WT pairs. This reasoning may be extended to find clustered sets of WTs subject to the same event. For other protections (FOL, MWS, GTT, MCV and BIL), the protection tripping simultaneity is not so relevant as in the voltage case.



a) full matrix representation



b) representation without diagonal matrix entries

Fig. 10. Annual duration of time-sequence simultaneity between 31 WTs in the VOL protection case.

VI. Conclusions

This paper has addressed the determination of wind turbine availability in a wind power plant, highlighting the specific impact of different types of failures as indicated by the tripping of the corresponding protections.

The analysis based on experimental data taken from wind turbines of equal manufacturer, type and size in actual operation conditions has clearly indicated a huge variety of operating conditions, with clear differences between the individual wind turbines. This variability has been investigated to construct a probabilistic model of the occurrence and duration of protection tripping. This model has been structured in such a way to represent the possible simultaneity of the protection tripping events.

On the basis of the results obtained, specific procedures can be developed for estimating the wind power plant reliability, taking into account the significantly different characteristics of the individual WTs and simultaneity of the protection tripping. The formulation of such a procedure and the related results will be reported in a future paper.

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VIII. Biographies

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