ICE ACCRETION AT ACQUA SPRUZZA AND ITS EFFECTS ON WIND TURBINE OPERATION AND LOSS OF ENERGY PRODUCTION

G. Botta[(1)], M. Cavaliere[(1)], H. Holttinen[(2)]

[(1)]ENEL Research, Renewable Energy Unit, Via Volta 1, 20093 Cologno Monzese, Italy
[(2)]VTT Energy, P.O. Box 1606, FIN-02044, Finland

Abstract

The Acqua Spruzza test site has been constructed and operated by ENEL to investigate the feasibility of wind plants in very hostile climate. The research activity, started at the end of 1995, includes regular monitoring of the operation of wind turbines and of the wind and climatic conditions. An estimation of the icing time at Acqua Spruzza has been performed through the analysis of more than two years 10-min meteo-anemological data. During that period, the behaviour of the wind turbines has been carefully observed, especially in cold months. The lessons so far learned concerning wind turbine operation in such an environment will be discussed.

1. INTRODUCTION

The wind measurements carried out in Italy by ENEL since 1979 have shown that the best wind resource is found on the ridges of Central and Southern Apennines. The full exploitation of wind energy also in other countries often requires the use of mountainous sites, where the highest wind resources can be found and, therefore, the economic competitiveness of wind energy is likely to be attained. Mountainous areas, located above 1000 m a.s.l, are usually characterised by complex terrain and harsh climatic conditions with heavy icing, snowfalls, high turbulence and high vertical component of wind speed. The performance of the wind turbines and their loading could be greatly affected by such an hostile environment; in particular, ice accretion can potentially create significant troubles. The need for research about the feasibility of wind plants and the viability of present commercial medium-sized wind turbines in mountainous locations led ENEL to the construction of a mountain test site at Acqua Spruzza on the Apennines.

2. THE ACQUA SPRUZZA TEST SITE

The construction of the Acqua Spruzza test site started in 1994. The climatic conditions of the site meet the requirements to carry out an experimental research programme in hostile terrain; in particular, heavy snowfalls and ice accretion usually happens in winter.

The plant is located on the Apennines, in the Commune of Frosolone (Molise Region in Central Italy), at an average altitude of 1350 m a.s.l., and involves an overall area of about 250000 m^2. It comprises eight machines of four different models, for an overall capacity of 2440 kW (Fig. 1). The models implement different wind power technology (e.g. one, two and three blades made of different materials, rigid and teetered hub, etc.). All the machines are standard models: therefore they have not been equipped with any heating device for sensors or for other turbine components. Two wind measuring masts have been installed with several types of anemometers, heated and unheated, as well as temperature, icing, solar radiation and humidity sensors [1].

Fig. 1 - Top view of the Acqua Spruzza test site

The research activity, started at the end of 1995, is contributing to some research projects funded by EU DG XII under the Joule III Programme and, in particular for the icing monitoring, to the "WECO" Project, where ENEL acts as subcontractor of VTT.

Data acquisition includes the regular monitoring of the operation of wind turbines and of the wind and climatic conditions. Campaign data has been recorded from some turbines equipped with dedicated acquisition systems [2]. Despite the problems suffered by the acquisition systems, due to the severe and frequent lightning strikes, a significant amount of both summary and campaign data have already been collected.

3. ICING AT ACQUA SPRUZZA

An estimation of the icing time at Acqua Spruzza has been performed by analysing more than two years of 10-min data, comprising data from an on/off Rosemount ice detector installed at about 5 m a.g.l. at the meteorological mast 1. In the detector the sensing element detects icing by magnetostrictive oscillation: as icing occurs, the natural oscillation frequency decreases. Whenever an icing event has been detected, deicing heaters are activated for 90 seconds, after which the icing sensor has to be cooled for some minutes before a new icing signal can occur. The sensor is also used to monitor the loss of the grid, which is quite frequent at the site: this information helps in data analysis, allowing the uncorrected data to be discarded.

The icing time has been estimated for the winters 95/96 and 96/97 in two ways. First the 10-minute intervals where at least one icing incident has been detected by the sensor are counted and grouped on a month by month basis. The sum of the counts gives then a first estimation of the monthly icing time. It can be supposed, however, that when rime ice forms on the structures, it is not easily shed off. For this reason, an additional estimation of the total icing time affecting the wind turbine production has been performed: the 10-minute values starting with ice detector signal and ending with temperature back in + 0 ^{o}C have been counted. This naturally results in a longer time estimate as compared to the first way of counting, and can be partly misleading as the ice can be shed off the blades before melting away. Probably the real icing time is somewhere in between these two icing times.

The estimated icing time at Acqua Spruzza is presented in Fig. 2: icing conditions occur 20 - 100 hours per winter month, while, if the ice accreted during icing conditions stayed at the blades until the temperature was back above zero, the total icing time affecting the production of wind turbines would rise up to 100 - 300 hours per winter month. It can also be seen that the same amount of icing incidents can lead to different icing time affecting the wind turbine (for instance February and March '96), depending on the temperature after icing events.

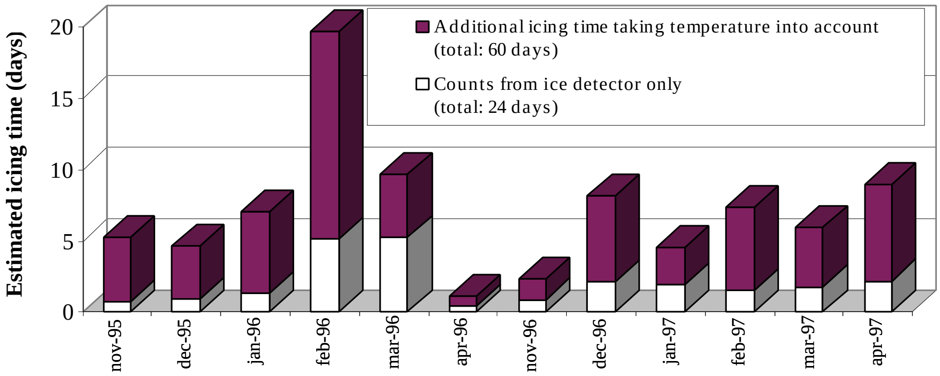

Fig. 2 - Estimated icing time at Acqua Spruzza

It is also interesting to point out that the wind speeds during icing conditions and during the time of frost after them are usually quite high (Fig. 3). This means that, when icing results in wind turbine unavailability and/or reduced power output, the loss of production can be quite significant.

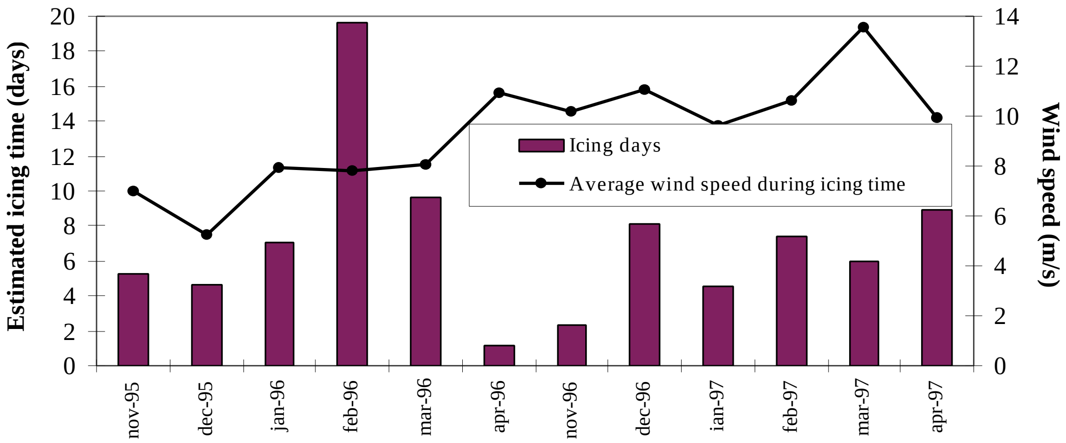

Fig. 3 - Monitored wind speed at Acqua Spruzza when icing occurs

4. WIND TURBINE BEHAVIOUR IN COLD CLIMATE

During the last two years of operation, the machines behaviour has been carefully observed, especially in cold months. Significant problems typical of the operation in mountain sites occurred in winter, which confirmed that special care should be taken in designing both wind turbines and relevant instrumentation for such an environment.

Icing can happen during either wind turbine operation or standing-by. Usually it occurs first on the nacelle mounted anemometer, and then on the blades. Depending on the initial state of the machine when icing occurs, different situations have been observed:

- wind turbine in stand-by and cup anemometer completely blocked by ice: the machine is prevented from operating until deicing of the anemometer occurs, because the control sees zero wind speed;
- wind turbines in operation and cup anemometer partially iced: anomalous variation of generated power, along with an unstable pitching activity, has been observed above the rated wind speed for those pitch-controlled machines which use the nacelle wind speed as an input to set some control parameters (Fig. 4); this was induced by the incorrect wind speed value given by the nacelle mounted anemometer;
- wind turbine operating and wind vane blocked by ice: the machine cannot follow the changes of wind direction; this in turn results in anomalous operations, reduction of energy production, high vibrations, stop of the wind turbine or off-design operation (e.g. operation downwind for upwind wind turbines, or viceversa);
- wind turbine in stand-by and heavy ice accretion on the blades: in one case, when the wind speed increased beyond the cut-in value, the rotor started to rotate in the opposite way, i.e. the leading edge of the blade acting as trailing edge and vice-versa;
- ice accretion on the blades: the shape of blade itself is changed and, therefore, its aerodynamic performances; this can prevent the machine from starting or, if the wind turbine is already operating when icing starts, can affect the energy output on one hand and make the machine operating in off-design condition on the other hand, often finally resulting in alarm status.

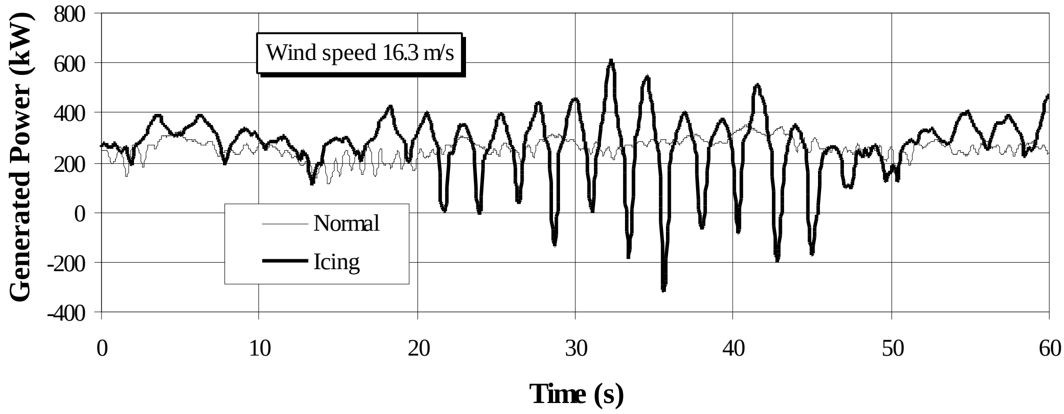

Fig. 4 - Anomalous oscillations of generated power above the rated wind speed

In Acqua Spruzza most problems have been caused by icing of anemometers and wind vanes, which , if partially or completely blocked, do not measure the correct wind speed and direction. These problems could be avoided, in principle, by using heated equipment; in that case, however, if no heating system is used for blades, this solution could allow the wind turbine to operate with heavy icing on blades and, thus, in off-design condition.

The wind turbines behaviour during icing usually results in significant unavailability time (also depending on the kind of the failure caused) as shown in Fig. 5, where ”icing days” is the number of 10-min ice incidents plus the time of frost after them, as specified in the previous chapter 3.

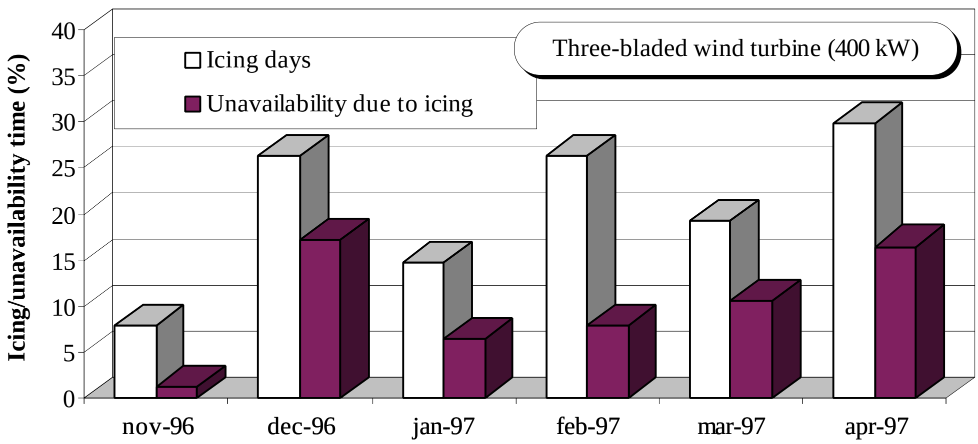

Fig. 5 - Estimated icing effect on a wind turbine availability at Acqua Spruzza

A clear correlation between unavailability and icing time can be noticed from Fig. 5.
The difference between the icing and unavailability time can be partially explained by the fact that the actual icing periods are somewhat shorter than those estimated.
Another important reason for that is the continuous presence of ENEL personnel at Acqua Spruzza, ready to remove the alarm cause and re-start the machine as soon as they can (it is not always possible, because sometimes the bad whether conditions do not allow the operators to reach the site). It therefore can be supposed that unavailability due to cold climate of the same machines would be much larger if they were installed in a not-attended plant.
It is also worth noting that the reported figures only approximates the actual unavailability; in fact, since they are provided by the machine controller, they refer to conditions in which failures or malfunctioning of some components prevented the wind turbine from operating, but can not take into account conditions in which, even though machines appear to be available, nevertheless they are not allowed to operate due to the false wind speed input to the controller because of icing of the nacelle anemometer.

Moreover, part of lost energy is also to be ascribed to the reduced power performance generated by ice accretion on blades. This has sometimes been observed during heavy icing conditions (Fig. 6), along with a reduction of the typical periodic power variation, as resulted from the power time series spectral analysis.

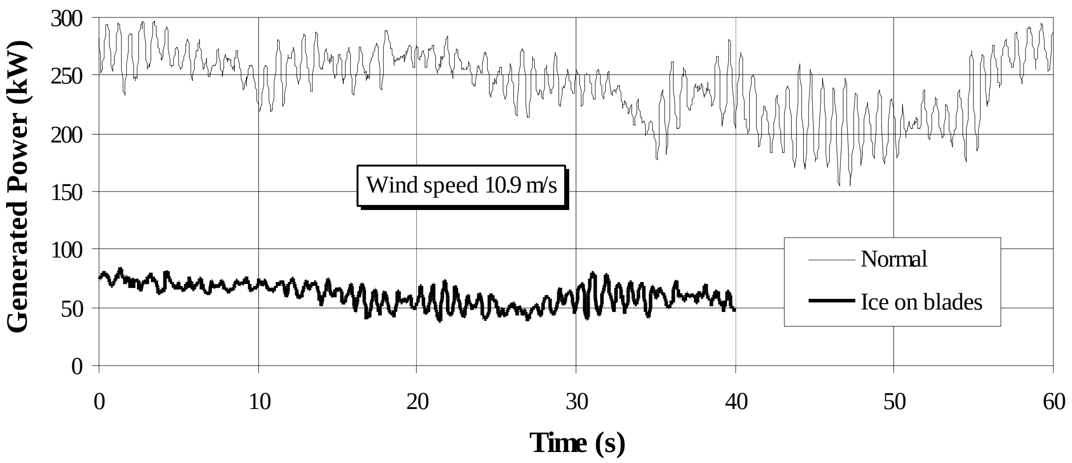

Fig. 6 - Reduced power output in heavy icing conditions

5. LOSS OF ENERGY PRODUCTION DUE TO ICING

According to the observed wind turbines behaviour, the loss of energy production in cold months in sites like Acqua Spruzza can be quite significant, especially because the mean wind speed in icing periods often results equal to or larger than 8 m/s.

Assuming that icing time results in wind turbine unavailability and a total loss of energy, the possible loss of energy production has been estimated for the wind turbines installed at Acqua Spruzza, by calculating the expected production during icing time. This calculation has been performed using the wind data recorded by heated anemometers in winters 95/96 and 96/97 along with the measured power curve in normal conditions.

The month by month result for a reference machine is reported in Fig. 7. The same calculation has been performed for the other wind turbine models; the results have been summarised in Table I. It can be noticed, that if icing would have resulted in full wind turbine unavailability, the energy lost in cold months could have been as high as 19% of the expected annual yield.

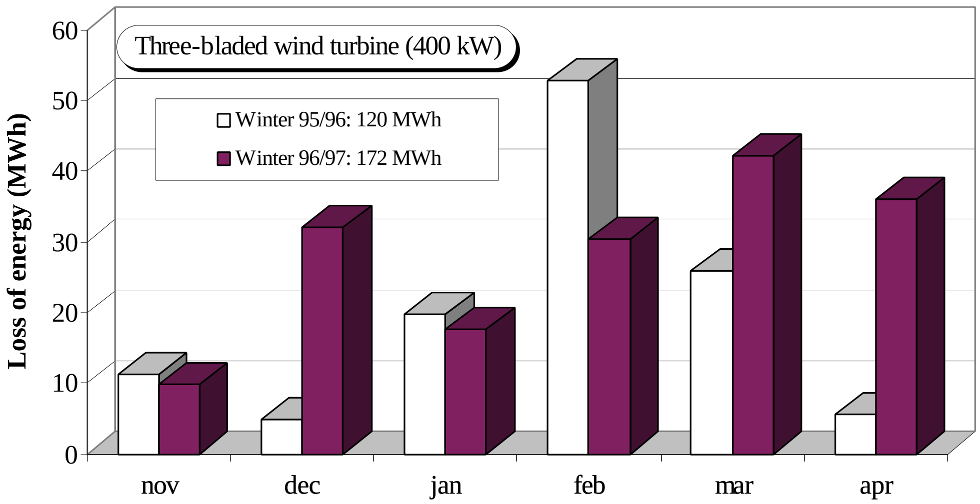

Fig. 7 - Possible monthly loss of energy production due to icing for a reference wind turbine at Acqua Spruzza

Table I - Possible loss of energy production due to icing for different wind turbines

	Winter 95/96		Winter 96/97	
Wind turbine model	**MWh**	**% of an. yield**	**MWh**	**% of an. yield**
One-bladed wind turbine (200 kW)	82	14	90	15
Two-bladed wind turbine (250 kW)	95	15	118	19
Three-bladed wind turbine (400 kW)	120	12	172	19

Although some uncertainties are to be taken into account when making this calculation, mainly related to the wind speed measurement errors, due to the complex terrain characteristics and the sensitivity of ice-free anemometers response to topography, nevertheless the above figures can be considered fairly representative of the actual situation. This means, for instance, that a mountain site like Acqua Spruzza having an annual average wind speed of 7.2 m/s should be considered, from an economical point of view when planning a wind farm, as an equivalent site of about 6.5 m/s, if standard machines without any protection against icing (e.g. heating systems) are to be installed. Fig. 8 shows for one of the best performing machines at Acqua Spruzza the comparison between the energy actually lost in cold months, calculated as the difference between the estimated and the actual monthly energy production, and the estimated possible loss of production: not all the energy production was lost for that wind turbine in icing periods 96/97, but a large part of it, despite the fact that Acqua Spruzza is an attended test site.

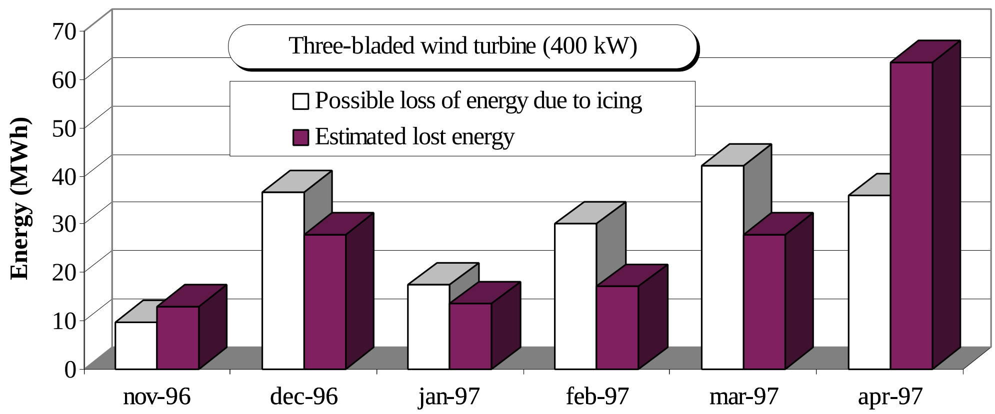

Fig. 8 - Predicted and observed loss of energy production in icing conditions

It is worth noting in Fig. 8 that the observed lack in energy production in April ‘97 is not entirely due to icing, but also to other causes of machine unavailability. It is also interesting to notice, by comparing Fig. 5 and Fig. 8 which refer to the same wind turbine in the same period, that even in those months when the wind turbine unavailability due to icing seems to be quite low and much shorter than the icing time (for instance November, January and February), the loss of energy production can be quite significant, for the reasons explained in the previous paragraph. This confirms that the mere information, provided by the controller, on the wind turbine availability in cold months can not be sufficient to characterise wind turbine performances.

6. CONCLUSION

Despite the problems due to very hostile operating conditions, suffered by both wind turbines and acquisition systems at the Acqua Spruzza test site, the monitoring activity and data reduction and analysis so far carried out have provided interesting results.

On-field observations indicate that icing can largely affect the energy output of wind turbines without modifications.
From the utility point of view, this means that these effects should be carefully taken into account when planning a wind farm construction, because the energy yield of a mountain site can be significantly lower than expected from the wind campaigns (from 10 to 20%).
From the manufacturers point of view, special care should be taken in designing both wind turbines and relevant instrumentation for hostile climate. For example, most problems could be avoided by using proper heating system both on the nacelle mounted anemometers and on blades, provided that these systems are reliable and cost-effective.

REFERENCES

[1] Botta, C. Casale, M. Cavaliere, "The Acqua Spruzza wind turbine test site", Proceedings of BOREAS II, Pyhatunturi (Finland), March 1994.
[2] Botta, C. Casale, M. Cavaliere, E. Lembo, "First experience at the Acqua Spruzza test site", Proceedings of EUWEC '96, Goteborg, Sweden, May 1996.