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Original Article

The Impact of Abnormal Weather Conditions on the Breakdown of Small Wind Turbines in Jordan

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Abstract *- This paper summarises the role and status of wind energy in Jordan. The performance of small-scale wind turbines installed by residential customers is discussed. The leading causes of minor and significant turbine faults are studied. These turbines are usually installed and connected to weak distribution grids in rural areas. Therefore, a particular focus is given to the main reasons for turbine failure, including harsh weather conditions, design inadequacy and grid instability. The impact of gusts on the wind turbine breakdown is given particular attention during the analysis of fault events. Since most wind farms in Jordan are installed in desert and semi-desert areas, the present work has deeply discussed the influence of high temperatures and intensive sand storms on the degradation process of wind turbine components. In all considered cases, the investigation focuses on the relationship between the defect development and the imperfection of the turbine's elements. The results obtained from inspecting small and large turbines are of significant importance to all parties, including the manufacturers interested in improving their future designs and materials of such turbines. Finally, it is expected that the feedback of this study will be highly appreciated by all players in the wind energy market in the Middle East area, which shows indications of moving from an oil-exporting business to a renewable energy business.*

Keywords *- Wind turbines, Weather conditions, Performance, Grid, Breakdown.*

1. Introduction

Wind has been a good energy source for hundreds of years. Historically, almost all nations have employed wind energy in their lives in one way or another. Some people have used wind energy to propel large sailing ships or irrigate crops, whereas others have used it to grind seeds and pump water. However, Wind Turbines (WTs) use for electricity generation has only started in the last century. Denmark was the first country to use the wind for such a purpose. The Danes were using a 23 m diameter WT in 1890 to generate electricity, and by 1910, several hundred units with capacities ranging from 5 to 25 kW were in operation in Denmark [1].

Since the power output of the WT is proportional to the cubic value of wind speed, the best locations for such turbines are remote open areas with rich wind resources [2]. However, the instantaneous sharp increase in wind speed leads to mechanical stress on the turbine shaft and blades. Therefore, matching the wind speed profile with the wind turbine design and structure is necessary. To achieve this goal, a complete knowledge of all weather conditions prevailing in the turbine area is required for a correct performance and integrity evaluation. However, due to the complexity of short-term weather forecasting, the turbine designers usually rely on historical weather data to generate an hourly wind speed profile. Therefore, manufacturers who do not adequately account for the impact of abnormal weather conditions on the design and do not precisely select the proper materials usually face a high failure rate for their turbines in future.

With the growth of the wind turbine industry, researchers' interest in such turbines' performance has increased. One of the essential topics in this field is the assessment of the integrity of such turbines under harsh conditions. Chen et al., for instance, have studied the structural integrity of wind turbines impacted by tropical cyclones using a case study from China [3]. Using finite element analysis, they have predicted the rotor blades' and tubular towers' failure modes and locations.

Papadakis et al. have introduced a comprehensive analysis of damage to wind turbine blades since they are the structure's most intensively stressed components [4]. They have claimed that the edges can be exposed to strong storm winds, raindrops or hail, falling with velocities higher than 100 m/s, lightning, repeated wind loads, and shear effects, which can introduce intensive hammer or fatigue loads, potentially causing several different types of structural damage. Some authors have shown that the wind turbine damage frequency to all mechanical systems and structures is almost equal, whereas others have focused on intelligent techniques [5, 21, 22]. Their experience for 15 years has covered all failures of mechanical and electrical components. Finally, Ma et al. have introduced a historical overview of wind turbine tower collapse cases [6]. They have discussed various types and causes of wind turbine collapses gathered from different resources over several years.

Despite the abovementioned research discussing the collapse of wind turbine elements, the challenges posed by harsh weather conditions have not been adequately addressed in the literature. The interest was mainly focused on the failures of large wind turbines rather than on small units. Therefore, the current study aims to introduce other aspects of failure mechanisms, especially those related to abnormal wind speeds, intensive sand storms and high ambient temperature.

After this section, the paper will introduce the characteristics of weather in Jordan and an overview of wind energy status, including the large-scale and small-scale wind farms and the particularity of climate in Jordan. The third section will discuss the current problem and its impact on the small wind turbine industry. The fourth section will present the study results, supported by several samples and illustrations of turbine failures. Section five will discuss the obtained results and explain the failure mechanism of each case. The paper will end with the conclusions and a list of references.

2. Renewable Energy in Jordan

Although Jordan is not a big country in population and area, it has several vital elements enabling it to be one of the crucial states in the Middle East region. Jordan's strategic location and political stability are among several significant factors which have increased the investment process of renewable energy in this country. In terms of area, the government provides an essential link between Asia and Africa continents through the Red Sea. Therefore, the 400kV submarine cable operated in 1997 between Egypt and Jordan is the only electrical interconnection linking these two continents. This project has enhanced the transmission system in Jordan and formed a milestone for future connections with neighbouring countries.

Despite the abovementioned achievements, the country has difficulty securing its primary energy resources. According to reliable references, the lack of fuel to operate power plants was a stiff barrier, challenging the Jordanian economy for several decades [7, 8]. Although the country is adjacent to several oil-rich states, all search attempts to find enough fossil fuel resources were unsuccessful. Therefore, when oil and gas prices go up in the international market, the electricity cost sharply increases, creating a severe economic problem for the country. As a result, Jordan is one of few countries where a significant portion of its budget is spent on importing fuel from oil-producing states. Moreover, the political instability in the region has increased the flow of refugees to Jordan and aggravated the country's weak economic situation. The result was a significant decay in the number of energy projects and, consequently, a remarkable decrease in the income of Jordanian people.

Given the above facts, the country's decision to go for renewable energy was strategic. The success in this field was in two forms: legislative and technical. A set of regulations and rules were issued to encourage and control renewable energy projects in small, medium and large- scales. This step was necessary for attracting investors from all countries and establishing a solid base for renewable energy in Jordan. Technically, several successful sizeable renewable energy projects were built in a very short time.

The rich experience gained in the previous decades to attract independent power producers for the Jordanian energy market successfully created a strong base for a renewable energy industry in Jordan. This approach has led to successful power purchase agreements, reliable rules and flexible guidelines governing renewable energy development.

Therefore, a grid code was set for renewable energy to parallel transmission and distribution codes. Jordan was a pioneer country in the Middle East in launching a new renewable energy law and encouraging tax-free trading of renewable energy equipment. Therefore, the number of renewable energy projects connected to the transmission and distribution networks in the last three years has exceeded the target. More than 26% of the daily load is from renewable energy resources. Finally, the significant growth of renewable energy in Jordan is expected to play a vital role in the energy market of several Middle East countries.

3. Problem Description

Despite the extensive use of renewable energy in Jordan, there is a lack of experience in specific fields, especially those related to technical issues of wind energy systems. This is attributed to inadequate training on advanced turbines, which were extensively installed in a very short time in the last five years.

Therefore, several wind farms were consecutively connected to the national grid without a deep focus on the long-term impact of such integration. When wind energy is compared to the PV system, in terms of design, operation and maintenance, it is easy to find that wind energy needs more investments, efforts, controls and technical skills than PV systems.

Jordan has different areas with different weather conditions prevailing at the same time. Although there are no frequent wind storms, some areas have high wind gusts, which might exceed 30m/s. Due to the variety of control schemes applied to small wind turbines, they respond to such gusts differently. In the case of large units with robust speed control, the blades take action to benefit from good wind, provided that it is within the acceptable speed. Such turbines stop working when the wind speed exceeds certain limits and return to regular operation when the gust ends.

Figure 1 shows the ultrasonic/anemometer, which sends a command to the control unit inside the turbine to take the required action [9]. Compared with large wind turbines, which are used for commercial purposes, small teams have no such advanced control due to their simple construction, cheap cost, and limited use. Such turbines depend on specific shapes of vanes to change the direction of blades and to keep the system in a safe mode, as shown in Figure 2. Therefore, the response of such turbines to a sudden change in the speed and direction of the wind may not be fast enough to protect the unit from the mechanical damage.

Fig. 1 Wind speed measurement and control elements in large WTs

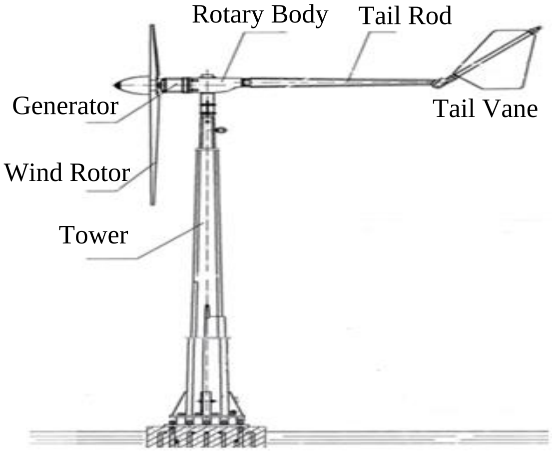

Fig. 2 Small wind turbine components with tail vane

4. Results

Excessive and abnormal wind speed can cause damage to the turbine blades and severe breach to its mechanical system. Figure 3 shows a breakdown of the rotary body of a 2kW WT due to an abrupt change in wind speed. This accident was reported in one of the windy sites in Jordan and resulted in apparent damage to contactors, brushes, brush holders and other parts, as shown in Figures 3-7.

Fig. 3 Damage in the rotary part of a 2-kW wind turbine

Fig. 4 Damage in the internal shaft of rotary part of wind turbine

Fig. 5 Damage in the brushes and brush holders inside the rotary part

Fig. 6 Damage in the shaft, holding the brushing system

Fig. 7 Loss of contacts due to shaft damage in small wind turbine

Although all WT components are theoretically exposed to damage, the blades are more likely to break down. This can be attributed to their function of receiving the wind and absorbing its mechanical power to produce the required electrical energy. Although these blades are designed to withstand all weather conditions, they are sensitive to the strong wind.

Figures 8 and 9 illustrate two pictures of damaged blades, which were exposed to extreme wind speed, whereas Figure 10 shows a malfunction in the turbine rotor. The failure appears as an apparent wear of a three-arm metallic base to fix and hold the turbine blades.

Fig. 8 Mechanical failure in the middle of the turbine blade

Fig. 9 Mechanical failure at the end of turbine blade

Hot weather is a common condition affecting the blade surface's quality and sustainability. As most of Jordan's land is desert, there is a persistent need for an energy source to settle people down. Therefore, most of the wind farms are placed in less populated areas. During calm summer months, the turbine blades do not rotate for hours. Thus, the direct sun radiation heats them and causes long-term weakness and damage. Although the wind motion is expected to cool the blades and neutralize the defect, the experience has shown that it will continue to grow once the failure is initiated. Figure 11 illustrates how the blade surface started to be affected by non-uniform swelling spots.

Fig. 10 Failure of the metallic bracket holding the blades

Fig. 11 Sign of blade ageing due to increase in temperature

Another important mechanism affecting the WT life is the presence of sand storms in desert areas. The sand degrades the WT blades by causing protrusions, tiny pits and roughness of the blade surface. The impact of the sand is a function of its size, composition, wind speed and humidity.

Although big-sized particles of sand cannot readily reach the blades of large WTs, smaller ones can easily hit such blades due to their significant height. Figure 12 shows a large WT affected by a sand storm close to the blade front edge, whereas Figure 13 illustrates blade damage caused by a gradual erosion process [11].

Fig. 12 Sand storm hitting large WT

Fig. 13 Blade damage caused by erosion process

5. Discussion

It is agreed by all researchers nowadays that WTs are essential energy sources in many countries. The energy yield of such turbines is mainly a function of wind speed according to Equation 1 [1].

$$P = 0.5\ \rho_a A_T V^3 \qquad (1)$$

Where P is the output of the wind turbine in kW, ρ_a is the density of the air in kg/cm^3, A_T is the swept area of the blades formed during their rotation in space, measured in m^2, V is the wind speed in m/s.

Since the behaviour of wind is randomly changed, the effect of its speed and, consequently, the energy yield will be challenging to predict instantaneously. Despite the development in wind prediction studies, there is still a severe challenge to the reliability of such studies. This does not reduce the importance of good prediction techniques to increase the profitability of wind energy systems. On the other hand, the attempts to capture more wind by enlarging the area of blades and increasing the tower's height can be accompanied by a further risk of damage under abnormal conditions. In modern privatized and deregulated power systems, the WTs' owner is only interested in the energy yield and the wind farm profitability, without paying attention to the importance of the robustness of the turbine itself or its control system.

In fact, the interest in the control system reliability depends on the wind turbine size and the type of electrical generator used in this system. Therefore, the manufacturers are not keen to add expensive control systems to small-scale WTs. Thus, these turbines are only equipped with simple and cheap control devices. Consequently, during high wind gusts, the devices responsible for controlling the speed and direction of wind turbines are subjected to abnormal mechanical and electrical stresses.

The problem will be aggravated when WT's frequent start and stop actions occur in parallel with sudden wind speed and direction changes. This can cause unacceptable stress on the mechanical parts of the wind system, eventually leading to severe long-term damage. The same effect can be noticed when the electric grid is not stable. Usually, the unstable grid causes several switching actions of WT start-stop within a very short time. This inevitably reduces the availability of the WT, decreases its performance and increases its failure rate.

When a small wind turbine is subjected to a strong wind, a high force acts on the rotating blades. The turbine will readily withstand wind stress if the blade material is strong enough and correctly designed and fabricated. However, the wind turbine market contains many products that have not been adequately tested and certified to cope with such harsh conditions. Therefore, the impact of a strong wind has appeared in the weak points, such as the rotating element joints, internal shafts, brushes holding cylinder, carbon brushes themselves and internal wiring, as shown in Figures 3-7.

Most conventional WT blades are fabricated from a composite material such as glass fibre-reinforced plastic, whereas modern composites are reinforced with Nanomaterials to exhibit good mechanical properties [12]. A special adhesive material is used to make a fibre-matrix bond. The composite materials are selected for their mechanical rigidity, stability for moisture, resistance to fatigue, high modulus elasticity and lightness [13].

However, the blade material is complex in design and manufacture and has meagre resistance against the forces perpendicular to the fibres. Therefore, when the wind gust's force exceeds the blade's mechanical potential, it breaks down, as shown in Figures 8 and 9.

The abnormal speeds are accompanied by high torques, leading to wear and enlargement of the metallic bracket holding the blades, as shown in Figure 10. At the same time, the blades, which are not instantaneously damaged by an excessive wind speed, become prone to serious internal fatigue, hidden cracks and gradual failure. [14, 21] This sensitivity to high wind speed is attributed to the design conditions, which involve contradicted mechanical requirements. This means the blades should be lightweight to facilitate their rotation during weak wind periods to produce more energy. In contrast, they should be fabricated from rigid materials to withstand the strong wind. Therefore, blades are usually made from composite material, combining lightness and rigidity characteristics to achieve these goals [4, 12, 14].

Although the main effects of high temperatures on the WT are the reduction of its efficiency and the overheating of its components, several theoretical and experimental research works have focused on the impact of high temperatures on the erosion of the blade material.

[15-17] Due to the big difference in temperature between day and night in desert areas, the blades are subjected to continuous expansion and contraction processes. This causes dryness, swelling and roughness of the blade surface and gradual cracks in the internal body. As it consists of composite material, the stretching and shrinking actions of the blade components will not occur in the same ratio, resulting in less integrity and displacement of the blade's internal structure, as shown in Figure 11.

On the other hand, the sand storms hitting the blade material can cause a roughness of its surface and long-term erosion of these blades, as shown in Figures 12 and 13. This roughness reduces the effectiveness of the airfoil in absorbing the useful power from wind and also leads to a decrease in the turbine's power output. Several research works confirmed this effect. [18-20] The influence level of the roughness on the airfoil performance depends on several factors, such as the frequency occurrence of sand storms, size and type of sand particles, degree and nature of the roughness, WT dimensions, tower height, blade material and others.

6. Conclusion

A detailed assessment of the impact of abnormal weather conditions on the functionality of small wind turbines was conducted. Various sources and causes of wind turbine failure, including high wind speed, excessive temperature and frequent sand storms, were discussed and analyzed. The individual WT elements, affected mainly by abnormal weather conditions, were specified. The main reasons for small WT failures were discussed, including simple and cheap control, inadequate design, lousy selection of materials, and low manufacturing quality and management applied to small wind turbines.

The current work has found that to improve the performance of small WTs and to reduce their failure rates, it is necessary to have enough information about the long-term prevailing weather conditions. The failure cases studied in this work were mainly real without relying on the others' theoretical information on small wind turbines. The data gathered, and the analysis were strongly related to small wind turbines installed in different areas in Jordan. Finally, this work has emphasized that the designers and manufacturers of such turbines must employ the obtained results.

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