Development of a Prototype Renewable Energy System and its Modification to Suit Middle East Applications

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Abstract—**This paper concerns with exploitation of renewable energy sources for meeting energy requirements of remote locations. It presents an investigation which is based on a practical project that was executed in collaboration between academia and industry. It involves design and installation of a prototype integrated renewable energy system which consists of two 15 kW wind turbines, electrolyser, fuel cell system (FCS) and the associated control equipment. It was installed at the furthest island of Shetland, North of Scotland, U.K. The philosophy used in designing this system is summarised as follows: During times of high wind, the electricity generated by wind turbines is normally greater than that required by site electrical load. The excessive amount of generated electricity is stored into Hydrogen by utilising an electrolyser which is then used to generate the deficient electric power by the FCS at times of low wind.**

I. INTRODUCTION *(HEADING 1)*

Oil crisis of 1973 due to Arab-Israeli conflict has led to sharp increase in oil prices. This in turn motivated industrial countries, for first time, to seriously consider exploitation of renewable energy sources such as wind, solar, marine etc. In order to make this happening, appropriate legislations were put in place. For example in 1978 Public utility Regulatory Policies Act (PURPA) has been published in the USA. ***This act has established the right for power producers (whether individuals or group of people) to use utilities' transmission and distribution networks to transmit electrical energy to another location***. The UK Energy Act which is similar to PURPA was published in 1983. Such legislations and other encouragements for competition have resulted in rapid increase of using renewable energy sources to drive small and medium electrical generators which are largely connected to utilities' distribution networks. However under certain circumstances such generators are also utilised to supply isolated networks. The latter is particularly common in remote locations which are far away form the Grid and consequently makes its connection to the grid expensive.

Exploitation of renewable energy sources (RES) has attracted and still continues to attract the attention of many countries world-wide. This is also helped by environmental pressures aiming at reducing CO_2 emission, which has recently become an important incentive for developing renewable energy sources globally. Recently it has been reported by the International Energy Agency that 46% global electricity would be from RES by 2050 [1], while Greenpeace International and European Renewable Energy Council forecasted the share of global electricity from RES would reach 77% by 2050 [2]. The share of global electricity from wind, according to Global Wind Energy Council would be 21-30% [3]. As with regard to solar, it was projected by Greenpeace International that electricity from solar would increase from 16 GW in 2008 to 180 GW of solar PV worldwide by 2030 [4]. Large percentage of electricity generated from RES would be non grid-connected. For example according to Greenpeace International about 40% of the 180 GW forecasted power systems solar electricity by 2030 would be non grid-connected.

In recent years several renewable energy systems have been developed to electrify remote locations in different parts of the world [5-6]. This paper presents an investigation related to exploitation of renewable energy sources aiming at meeting energy requirements of remote locations. This investigation is based on a practical project which was executed in collaboration between academia and industry. It was funded by the U.K. government, industry and local community. It involves designing and installation of a prototype integrated renewable energy system which consists of two 15kW wind turbines, electrolyser, fuel cell system and the associated control equipment. It was installed at the furthest island of Shetland located at the north of Scotland, U.K.

The philosophy used in designing this system can be summarised as follows: During times of high wind, the electricity generated by wind turbines is normally greater than that required by site electrical load. Consequently the excessive amount of generated electricity is stored into Hydrogen by utilising an electrolyser. The excessive amount of generated electricity is stored into Hydrogen by utilising the electrolyser which is then used to generate the deficient electric power by the FCS at times of quite/low wind.

II. SITE OF THE PROJECT

The system was developed and installed in Unst; the most northern island in Shetland located 200 miles from Scotland mainland. This makes it a truly remote area which is characterised by (i) having high wind energy resource. Fig. 1 shows a comparison between wind energy resource in Shetland and other locations in the UK and Denmark. It demonstrate that wind energy resource in Shetland is as twice as high the UK and Denmark locations [7] (ii) far from the grid and (iii) the cost of oil related products such as petrol and diesel could be as high as 20% more the UK mainland. This has led to opting wind turbine as power source for the considered system.

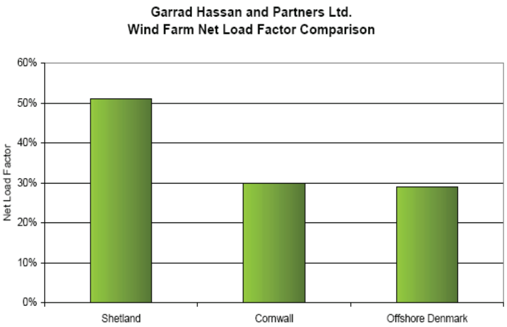

Fig. 1 Comparison between wind energy resource in Shetland, Cornwall (UK) and Denmark

III. PHOLOSOPHY OF DESIGN

The philosophy upon which the design of the system is based can be summarised as follows: During times at which wind is high the electricity generated by system wind turbines is normally more than needed by the site electrical load. The excessive amount of generated electricity is stored into Hydrogen by utilising an electrolyser. At times when wind is low or quite the resultant generated electricity constitutes only a fraction of load demand. The remaining electric power required by the load is obtained from the electricity generated by fuel cells which uses the stored Hydrogen as their input. The Hydrogen generated by the system can also be used for other applications such as powering the project site small electric car.

IV. SYSTEM COMPONENTS

Fig. 2 shows the details of the system. It basically consists of (i) a renewable energy system which comprises from two Proven wind turbines each drives a permanent magnet generator (PMG) rated at 15kW, (ii) back-up energy system based on Proton Exchange Membrane (PEM) fuel cell technology where the adopted fuel cell is rated at 5kW, (iii) an electrolyser based on Alkaline technology for hydrogen production, (iv) hydrogen storage system and hydrogen dispenser, (v) two electrical load; the first in a form of electrical heating system which can be directly supplied from unregulated DC supply and the second is an AC load and (vi) energy management control system.

The unregulated AC power generated by the two wind turbines is rectified and smoothed to provide a DC supply of up to 30kW on a common DC bus. The unregulated DC bus power is then used to either supply the 9KW inverter, the storage heating system, or the electrolyser depending on weather condition and also on load requirements. The management control system is specifically developed to prioritise the flow of power generated by the turbines. During periods of low electrical demand and high electrical energy generated by the turbines during high wind, surplus energy is directed to the electrolyser for generating hydrogen which is stored in the pressurised storage system. When the energy balance is reversed, the consumption of the load exceeds the electrical energy generated by the wind turbines. In this case, the fuel cell is operated. The fuel cell maintains the power supply to the AC circuit consumer unit through a 5kW inverter. During the time when the fuel cell is in operation, the electrolyser is switched off to minimise the parasitic loss in the system during light wind periods. However, the wind turbines even in the event of low renewable power generation continue to maintain the supply to the heating system. The latter is switched off only when there is no wind.

V. THE EXTRACTED MECHANICAL POWER FROM WIND

Theoretically the wind power available to be harvest by wind turbine is given by equation (1):

$$P_{th} = \frac{1}{2}\rho A v_w^3 \qquad (1)$$

Where, P_{th} is the theoretical wind power that can be converted to mechanical power by wind turbine, ρ is the air density [kg/m3], A is the area swept by wind turbine blade

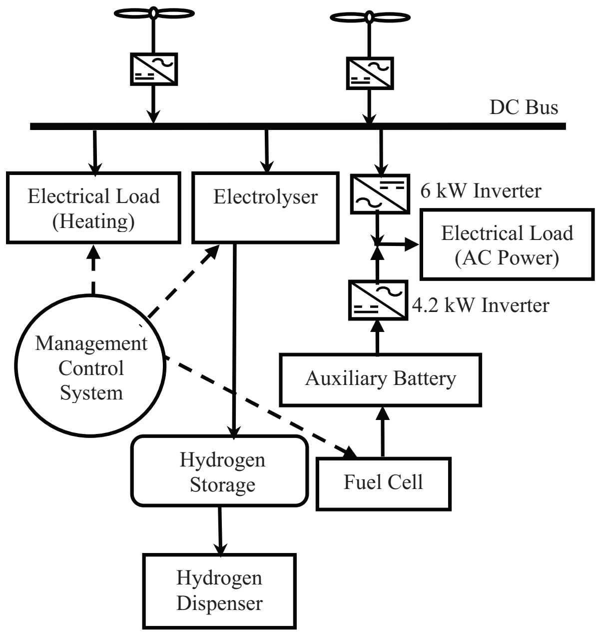

Fig. 2 Basic components of Unst integrated renewable energy system

and v_w is the wind speed [m/s].

The rotor diameter of wind turbines used in this project is equal to 9.4m resulting in a swept blade area of 69.4 m^2.

The actual mechanical power that can be extracted from wind is equal to theoretical wind power multiplied by the power coefficient of wind turbine such that [8]:

$$P_w = \frac{1}{2}\rho\pi R^2 v_w^3 C_p(\lambda, \theta_{pitch}) \quad (2)$$

Where, P_w is the actual extracted power from wind, R is the radius of wind turbine blade [m], and Cp is the power coefficient which is a function of tip speed ratio, λ, and blade pitch angle, θ_{pitch} [deg], where λ is given by:

$$\lambda = \frac{\omega R}{v_w} \quad (3)$$

Where, ω is the angular speed of wind turbine blade.

Figs. 3 and 4 show the power curve and the power coefficient curve specific to the adopted wind turbines [9]. It can be seen from Fig. 4 that the optimum designed power efficiency for the selected wind turbine occurs at wind speed of 8 m/s. The efficiency of wind turbine below this optimum speed is not of great importance as there is not much energy available to be extracted from airflow. On contrary at high wind speeds wind energy in excess of the design limits of electrical generator must be shed by the turbine. The process of power shedding can be understood by examining Figs. 3 and 4 related to the turbine power curve and the efficiency respectively. It is evident from these two curves that by the time the turbine reaches its rated power of 15kW at approximately 10 m/s, its efficiency has dropped considerably which ensures regulating the turbine output. Having low turbine efficiency is particularly important at high wind speed region where wind energy is high and the extracted amount of energy must be limited to the rated power of generator otherwise it would be damaged.

The best way to demonstrate how the two curves work together is by reference to Fig. 5 which shows a sample of a record of wind speed versus time at the project site and the corresponding wind turbine output [10]. It can be seen that although wind speed between hours 25 and 30 continues to increase the turbine output remains almost constant at 14 to 15kW. During the same period wind speed varies between 17 m/s to 26 m/s. With Reference to the efficiency curve of Fig. 4 it can be seen that the corresponding turbine efficiency is 7.5% to 2%. This means huge amount of wind energy is shed for the sake of protecting the generator from damage.

The best way to demonstrate how the two curves work together is by reference to Fig. 5 which shows a sample of a record of wind speed versus time at the project site and the corresponding wind turbine output [10]. It can be seen that although wind speed between hours 25 and 30 continues to increase the turbine output remains almost constant at 14 to 15kW. During the same period wind speed varies between 17 m/s to 26 m/s. Referring to the efficiency curve of Fig. 4 it can be seen that the corresponding turbine efficiency is 7.5% to 2%. This means huge amount of wind energy is shed for the sake of protecting the generator from damage.

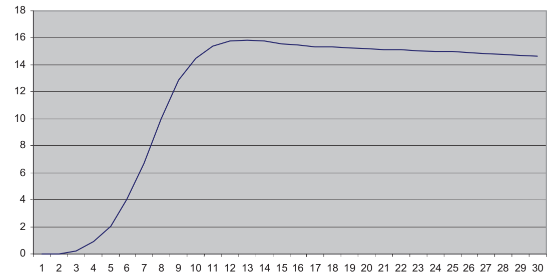

Fig. 3 Power curve for 15kW Proven wind turbine

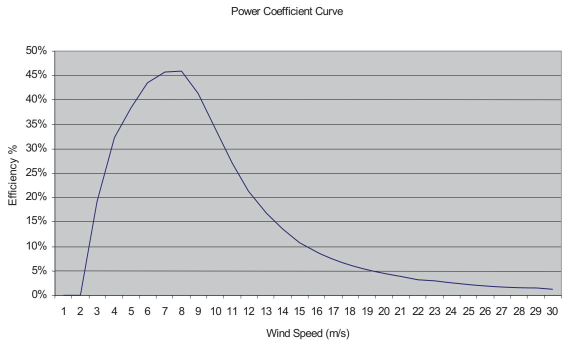

Fig. 4 Power Coefficient, Cp for 15kW Proven wind turbine

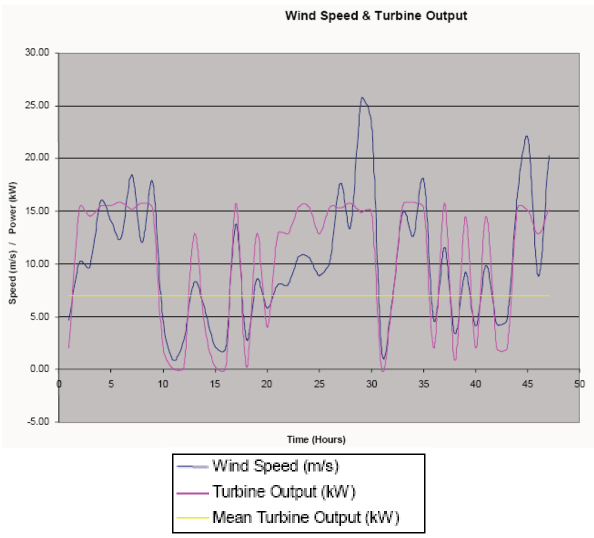

Fig. 5 Time-series wind speed and the corresponding simulated wind turbine power output

VI. Renewable Energy System For Middle East Applications

Lessons and experience learned from Unst prototype renewable energy system [7] can be used for the development and installation of similar systems anywhere in the word including Middle East after taking into account local dominant renewable energy resource. It is obvious that the dominant renewable energy resource in Middle East is solar radiation which is available in huge quantity almost everywhere. Similar to Unst island coloration between the energy demand and energy resource also exists in Middle East. However the energy demand in case of Middle East is in a form of cooling during summer time as opposed to heating during winter in case of Unst. Therefore a renewable energy system that suits Middle East environment would be similar to that shown in Fig. 2 but with replacing wind turbines and its interfacing AC/DC rectifiers by Photovoltaic arrays, which normally generate DC voltage, and DC/AC inverters respectively as shown in Fig 6. Further modification may be introduced depending on whether there is a need for hydrogen applications. If this is not the case the back-up system based on generation of hydrogen and fuel cell technology may be replaced a back-up system based on batteries. Final decision regarding which of the two options is to be adopted should consider factors such safety issues, economical considerations and staff training.

VII. Conclusion

Development of a prototype clean renewable energy system for electrical generation suitable for remote areas has been presented. It was installed in Unst Island located 200 miles from the UK mainland which is characterised by having high wind energy resource compared to other locations in the UK mainland and Europe. The system basically consists of a primary electrical generation source comprising of two 15kW wind turbines and a back-up electrical power source based on fuel cell technology. The latter is essential to meet the deficiency in the primary electrical power generation normally experienced at times when there is no wind or when its speed is low.

Modification of Unst renewable energy system to suit the clean energy resource available in Middle East which is solar radiation has also been discussed. Modification includes replacing wind turbines in case of Unst system by photovoltaic solar panels. The back-up power source may need to be also replaced by alternative one based on batteries depending on factors including whether hydrogen generation is needed, safety issues and economical consideration.

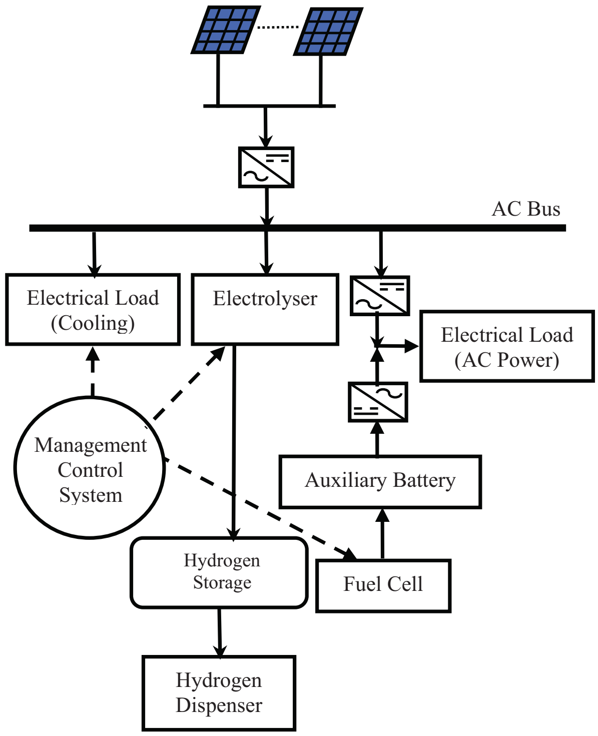

Fig. 6 Basic components of Middle East version of Unst integrated renewable energy system

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