AC 2011-972: A GREEN HYBRID POWER PLANT USING PHOTOVOLTAIC AND WIND ENERGY WITH POWER QUALITY IMPROVEMENT IN QATAR

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A Green Hybrid Power Plant using Photovoltaic and Wind energy with Power Quality Improvement in Qatar

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ABSTRACT A major challenge to using wind as a source of power is that wind is intermittent. Wind energy cannot be stored, and not all winds can be harnessed to meet electricity demands. Therefore, this energy source should be used with other types of energy sources to provide a continuous and reliable electrical energy source. In this paper, a solar power plant with a solar tracker is selected to hybridize with the wind energy source. Using the sun tracker will increase the energy absorbed by the photovoltaic panels which in turn will increase the efficiency. A hybrid power plant using solar energy and a wind power plant will be designed, and the results will be used for implementation in a pilot plant which will advance knowledge and education. The efficiency of the power plant can be improved by using power electronics and electric energy storage. The power conditioning unit combines the electric energy from both the solar power plant and the wind power plant. The dc output energy of the hybrid power plant will be converted to ac and will be synchronized with the electric power grid by the power conditioning unit. The AC output will be generated and controlled by the power conditioning unit which has multiple benefits of both generation of electricity with high efficiency and improvement of electric power quality.

1. Introduction

In recent years, there have been concerns due to global warming across the world. Therefore, most countries are working on using renewable energy sources and clean fuels like hydrogen. Their focus is on increasing the efficiency of fossil fuel conversions to decrease the global warming effect. Qatar, having high potential of solar energy and wind, can help these efforts by developing solar and wind energy power plants.

Solar cells power plants could be an alternate source of renewable energy for electric power production. Photovoltaic converters are important converters for the application of renewable energy sources because of the direct conversion of solar energy to electric energy. Their advantages include low weight and size, quiet energy conversion without any environmental effects, long life, and installation capability from small power (Watt) to large power (Mega-Watt) scales [1,2].

Wind energy can be used in Qatar by hybridizing it with another abundant energy source like solar energy. By integrating it with proper electric energy storage, a reliable and efficient renewable electric power plant can be obtained.

This paper introduces an effective solution by integrating a renewable energy source (i.e. solar energy) with wind power plant.

Other objectives of this paper are using renewable energy sources as reliable power sources with stand alone and grid connected capability which can improve distributed electric power quality.

The green hybrid power plant (GHPP) is significant because of the following:

- Using renewable energy sources.
- Using hybrid power plant with more than one type of renewable energy input improves reliability of the system that is compatible with environment.
- Providing a hybrid renewable energy power plant system which can be extended in power generation capacity by increasing solar panels or wind turbines.
- Improving power quality of the network by reactive power generation.

2. The Green Hybrid Power Plant (GHPP)

The Green Hybrid Power Plant (GHPP) proposed in this study combines solar energy power plant as a renewable energy source (using solar tracker array) with a wind power plant. A hybrid power plant using solar energy and wind will be designed and then the results will be used for setting up a pilot plant. The system efficiency and continuity will be improved by using power electronics technology and electric energy storage. The green hybrid power plant consists of the following systems: (1) Solar Power Plant (Photovoltaic Converter, 1 kW), (2) Wind power plant, 3 kW generator, (3) Electric Energy Storage, 48 kWh Storage, and (4) Power Conditioning Unit (Electric Power Flow Management using Digital Signal Processor and Switching Converters, 4 kW).

This power plant contains two types of renewable energy sources as input and a monitoring and controlling power conditioning unit that will deliver the generated electric energy to the utility grid and it also has an electric energy storage to improve the power quality and continuity of the plant output power.

The green hybrid power plant consists of the following main parts as shown in Figure 1:

1) Solar Power Plant (photovoltaic technology [2]),
2) Wind Power Plant,
3) Electric Energy Storage (rechargeable battery bank),
4) Power Conditioning Unit (power electronics and control [1])

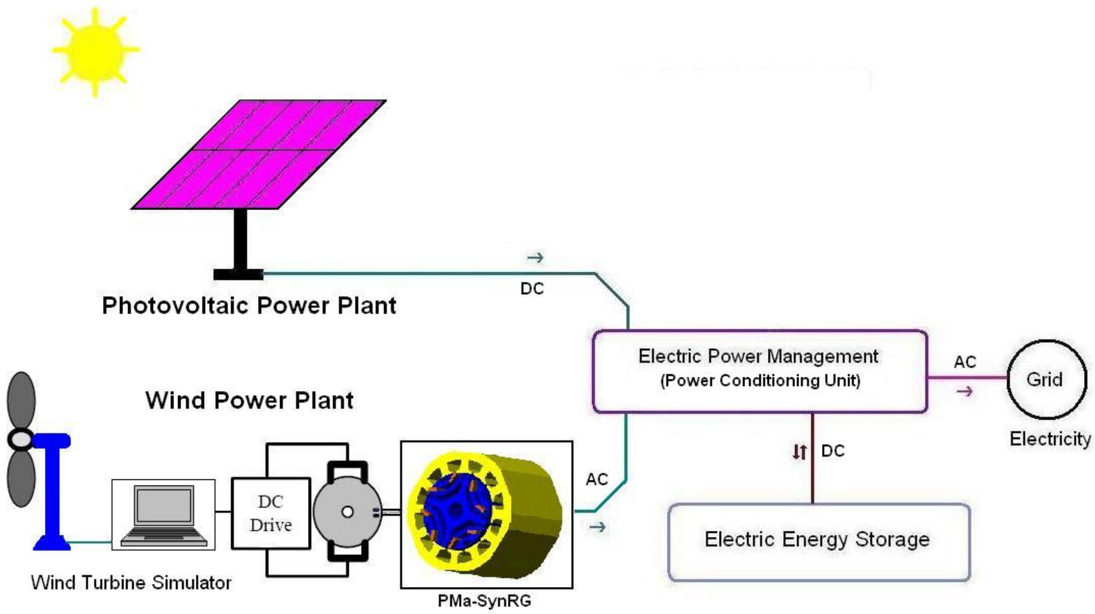

Fig.1. Green Hybrid Power Plant System (with wind turbine simulator which will be replaced by an actual wind turbine after fabrication and test of the generator)

The electric energy of the hybrid power plant will be continuous by using electric energy storage. The power conditioning unit combines the electric energy from both solar power plant and wind power plant. Using the power conditioning unit the output power of the hybrid power plant will be converted to AC that will be synchronized with the utility grid.

3. Solar Power plant

Solar cells convert the energy of light's photons to electric energy with efficiency between 5 to 25 percent without using thermodynamic cycle or active fluid. Solar cells can be light collector directly or can use light concentrators like mirror or convex lens. Nowadays, the commercial solar panels are available with more than 12% efficiency and can be used with advantages such as: relevant design and installation, quiet energy conversion, long life time with less maintenance requirement, easy transportation and light weight.

Due to high cost of solar arrays, a number of researches are done to increase the efficiency of the photovoltaic converters such as increasing the efficiency of solar cells, using solar tracker structure to follow the sun motion during the day, and using maximum power point tracker (MPPT). In recent years, due to market growth, the price of solar cell is decreased. Use of solar tracker can increase its efficiency by about 40% [2, 4, 5, 6, 7, 9, and 10].

The solar power plant consists of several solar trackers which depend on the solar power plant output with a few photovoltaic panels. They will follow the sun during the day and will generate electricity directly. By using solar trackers it is possible to increase the energy efficiency by about 40% in comparison with the fixed solar arrays [4]. To increase the efficiency of the photovoltaic power plant, special power management systems like solar trackers with maximum power point tracking capabilities will be analyzed. A typical photovoltaic power plant is shown in Figure 2.

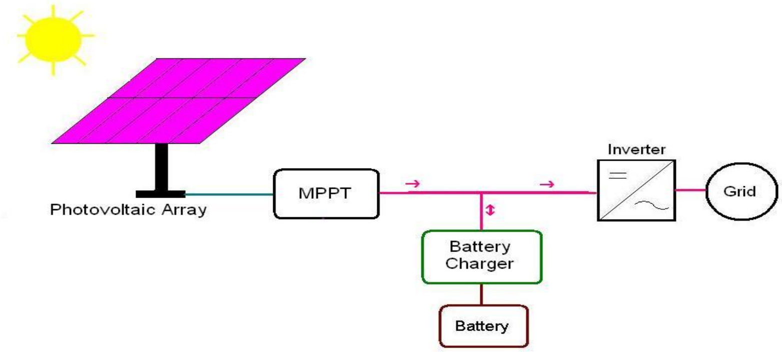

Fig.2 A typical photovoltaic power plant configuration

3.1 Solar Energy in Qatar

Because of the high potential of solar energy in Qatar, using this type of renewable energy will help to reduce dependency of generating electrical energy from fossil fuel and reduce the pollution of environment. The world solar energy potential has been shown in the Figure 3. Qatar is located in a region with the highest potential of solar energy as shown.

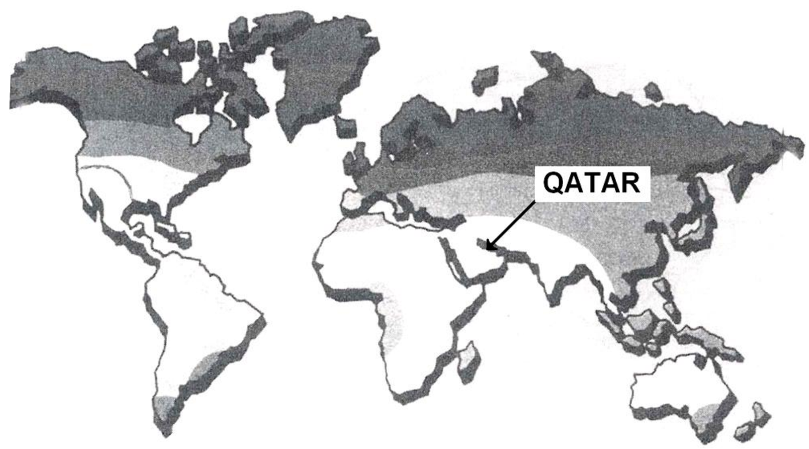

Fig.3 Solar Energy Radiation Potential on the World Surface

3.2 Photovoltaic Converter in Solar Power plant

Solar energy is a renewable energy source which can be converted easily and directly to electric energy using photovoltaic converters. The process of no movable mechanisms to convert solar energy to electric energy is called photovoltaic phenomena whereas the conversion device is called solar cell [3,4]. Figure 4 shows the equivalent circuit model of a solar cell which is a nonlinear device. By neglecting the internal shunt resistor in the model, the current-voltage characteristics of a solar cell can be obtained from (1) and (2):

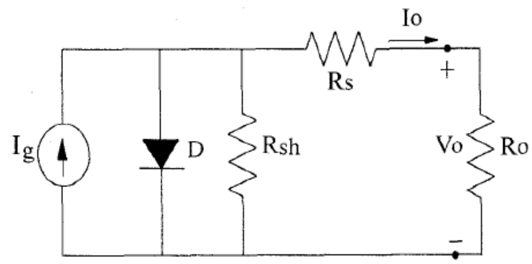

Fig.4. Simplified equivalent circuit of a solar cell

$$I_o = I_q - I_{sat}\left\{\exp\left[\frac{q}{AKT}(V_o + I_o R_s)\right] - 1\right\} \tag{1}$$

$$V_o = -I_o R_s + \frac{AKT}{q} \cdot In\left[\frac{I_q - I_o + I_{sat}}{I_{sat}}\right] \tag{2}$$

Where, Iq is light generated current, I_{sat} is the reverse saturation current, q is the electronic charge, A is a dimensionless factor, K is the Boltzmann constant, T is the temperature in Kelvin and R_S is the series resistance of the cell [5].

3.3 Effect of Sun Radiation Angle on the Solar Cells

Because of the low efficiency of the solar cells (less than 15%) and due to their high price with respect to other energy converters, it is important to convert and absorb the maximum electric energy from the photovoltaic (PV) arrays. Using movable PV array to follow the sun during the day and providing a condition that the solar light directly radiates on the solar cells will optimize energy conversion. The electric characteristics of the solar cells change due to the variation of the generated electrons with light intensity. Figure 5 shows the current-voltage characteristic of a sample solar cell [5]. The generated current by the solar cell has a large variation from light intensity changes. As a result, the output power of the solar cell can change and the photovoltaic array can generate electric power less than its nominal power.

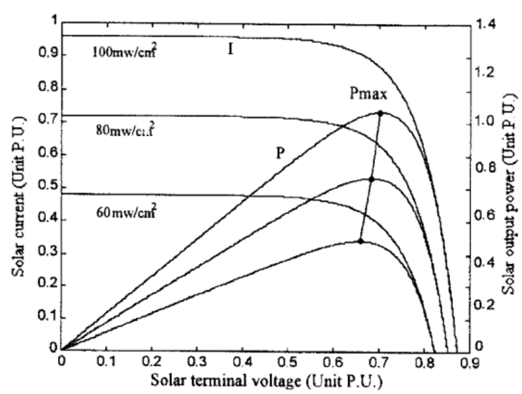

Fig.5: Variation of sample solar cell output characteristics with light intensity changes [2]

3.4 Electric Current Variation with Sun Radiation Angle

There is a traditional method to install the fixed PV arrays where usually they are installed with a tilt of the 90 to 100 percent of the installation place latitude directed to the South (in North Hemisphere). This type of installation causes loss of significant part of solar radiation energy because of the permanent reflection. The angle between light and the collector surface, and also the time length of the solar day, sun appearance time on the top of the solar collector, is shorter than duration of normal day especially in the summer. Figure 6 shows the effect of the light angle on the generated current on a sample solar cell.

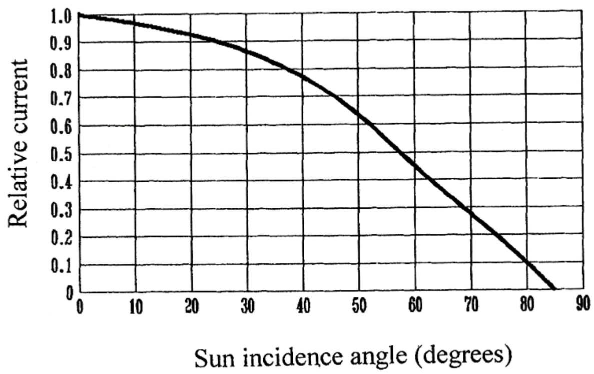

Fig.6: Solar cell current variation due to variation of the sun light radiation angel on the surface of the solar cell [2]

3.5 Using Moveable photovoltaic arrays to Increase Energy

In contrast with the fixed PV array, the solar collector (or PV-array) which follows the sun motion, can receive the maximum radiation and generates optimum energy because the sun light radiates perpendicular on the surface of the solar cells The result of using this kind of PV array is increasing the input of solar energy and the results are shown in Figure . The output powers of tracking and fixed photovoltaic arrays are compared. The energy increasing for a photovoltaic converter with tracking PV-Array is about 40% yearly that is significant [2].

Based on the above concepts, two-axes movable PV arrays will be analyzed with respect to the environmental condition of Qatar and will be used to increase solar energy absorption.

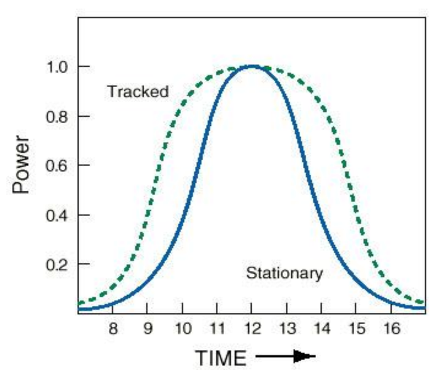

Fig. 7. Tracked photovoltaic panel output power compared to the fixed one.

Figure 8 shows the solar tracker implemented by the team to investigate the effect of tracking the sun using movable photovoltaic panel [2].

Fig.8 Two-axis photovoltaic tracker implemented by solar project team [2]

3.6 Specification of a 1 kW Photovoltaic Converter Systems

The main components of the photovoltaic power plant rated at 1kW are shown in Table 1.

Table 1. Components of photovoltaic power plant

Part	Nominal Power	Desired Efficiency
Photovoltaic Array	1 kW	Min 12%
MPPT	1 kW	95%
Sun Tracker (Dual Axes)	N/A	N/A
Battery Charger	Included in MPPT	-
Battery Storage	Not included	-
Inverter	Not included	-

4. Wind Power Plant

Wind energy is one of the most important and promising sources of renewable energy, mainly because it is considered to be nonpolluting and economically viable. At the same time, there has been a rapid development of related wind turbine technology. The installed wind power capacity in the world has been increasing at more than 30% per year over the past decade. The current surge in wind energy development is driven by multiple forces in favor of wind power including its tremendous environmental, social and economical benefits, the technological maturity, and the deregulation of electricity markets throughout the world, public support, and government incentives. Recent developments in wind power generation have provided an economically competitive and technically sound solution to reduce greenhouse gas emissions [10,11].

4.1 Wind Power Plant

Another renewable energy source which will be used in this project is the wind energy. Wind energy is the world's fastest growing renewable energy where the average annual growth rate of wind turbine installation is around 30% during the last 10 years [10]. Several researchers have investigated the feasibility of wind energy utilization in the Persian Gulf region [17–21].

Figure 9 shows the regional installed wind power where the growth of Asia is significant but not in the Middle East including Qatar.

Fig. 10. Global annual installed capacity 1996-2007 [10]

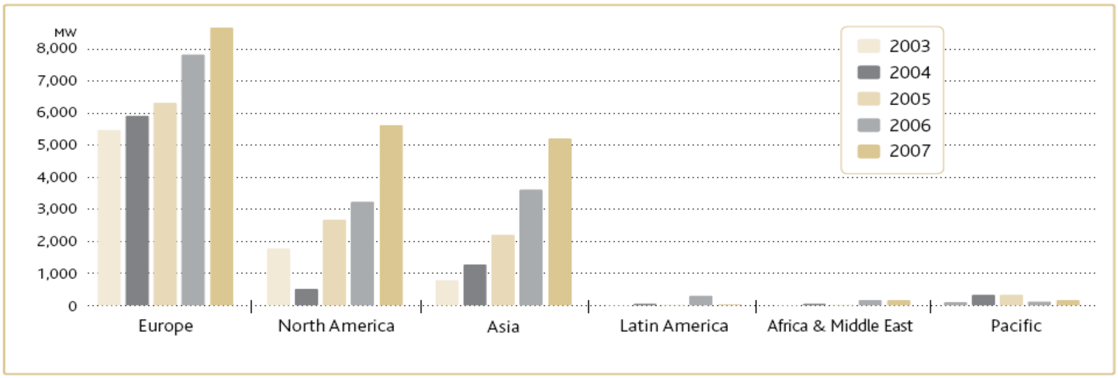

Fig. 9. Annual installed capacity by region 2003-2007 [10]

A major challenge in using wind as a source of power is that wind is intermittent and it does not always blow when electricity is needed. Wind energy cannot be stored (unless batteries are used); and not all winds can be harnessed to meet the timing of electricity demands. Due to the fact that electricity has to be generated exactly at the moment of demand, some other back up electric energy sources should be used. This energy source can be hybridized with other type of energy sources to provide a continuous and reliable electrical energy source [11].

An analysis is presented for the long term measured on-shore wind speed at Doha International Airport. A similar analysis is presented for the measured off-shore wind speed at the Qatari Haloul Island. For the on-shore measurements, the average annual wind speed (at 20 m height) was found to be about 5.1 m/s. On the other hand, for the off-shore measurements at Haloul, the average annual wind speed was found to be about 6.0 m/s. Since the minimum required wind speed for a wind park (at 20 m height) is about 3 m/s which is equivalent to 2.54 m/s at 10 m height, a typical turbine will operate about 75% of the time throughout the year on-shore and 80% off-shore [12-21].

These results indicate possibility of utilizing small to medium-size wind turbine generators installed even at much lower heights in Doha-Qatar. Based on these results, it is reasonable to use wind energy in Qatar.

4.2 Types of Wind Turbine Generator

Different types of wind turbine configurations are shown in [22]. It is clear that in some topologies gearboxes are required and direct power electronic converters to transmit the generated electric power to the utility grid are needed.

Permanent magnet generator is a good choice because it can work over a wide speed range and they can be directly connected to the wind turbine. The performance of PMs has been improved and the cost has been reduced in recent years. This makes the variable speed direct-drive PM machines with a full-scale power converter more attractive for offshore wind power generations [22].

The requirement for the development of inexpensive, flexible and reliable generator systems has expanded in the last few years. One of the inexpensive types of PM generators is the permanent magnet assisted synchronous reluctance generator. This type of generator uses much less permanent magnet in the rotor and can operate over a wide wind speed range with a better overall efficiency [24,37].

5. Electric Energy Storage

The energy density of lead-acid batteries is low, mostly because of the high molecular weight of lead. The temperature characteristics are poor. Below 10°C, the specific power and specific energy are greatly reduced. But this aspect cannot limit the application of lead-acid batteries for the storage energy in countries with hot weather conditions such as Qatar [34]. Therefore, lead-acid batteries will be used to store energies obtained from sun and wind and use them when they are mostly needed like during peak power load and during lack of wind and sun.

Electricity from the solar power plant can be generated mostly during the sunny day and also the electricity generated from wind power plant has changes during the wind flow change. But the output of the power plant should be continuous and reliable during 24/7. Therefore electric energy storage is also needed that could be used as an energy source for power quality improvement for utility grid. This electric energy storage can be a deep-cycle lead acid batteries, flywheels or ultra-capacitors. In this project, low-cost deep-cycle lead acid batteries will be used.

5.1 Stabilization of Renewable Energy Sources

To help renewable technologies like wind turbines, photovoltaic converters, and fuel cells become more competitive with fossil and hydroelectric power plants, their output can be stabilized with the use of electric energy storage systems. Energy storage systems can be used to follow loads, stabilize voltage & frequency, manage peak loads, improve power quality, defer upgrade investments, and support renewable energy sources. Figure 10 shows the power and energy handling capacity of some storage techniques which can be used for electric energy storage for further researches.

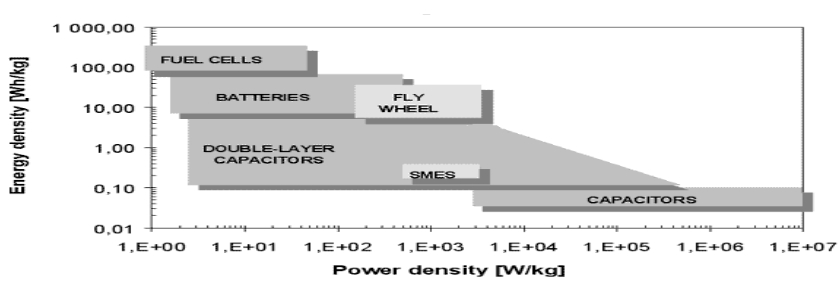

Fig.10. the energy storage and power handling capacity of some

alternative storage techniques [32]

5.2 Batteries

The lead-acid battery has been a successful commercial product for over a century and still is widely used as the electrical energy storage in the automotive field and other applications. Its advantages are: low cost, mature technology, and relative high power capability. The energy density of lead-acid batteries is low, mostly because of the high molecular weight of lead. The temperature characteristics are poor. Below 10°C, the specific power and specific energy are greatly reduced. But this aspect cannot limit the application of lead-acid batteries for the storage energy in countries with warm weather condition such as Qatar. Nickel is a lighter metal than lead and has very good electrochemical properties desirable for battery applications. There have been four different nickel-based battery technologies: Nickel/Iron, Nickel-Zinc, Nickel/Cadmium, and Nickel-Metal Hydride (Ni-MH). Lithium is the lightest of all metals and presents very interesting characteristics from an electrochemical point of view. Indeed, it allows a very high thermodynamic voltage which results in a very high specific energy and specific power. There are two major technologies of lithium-based batteries: Lithium-Polymer (Li-P) Battery and Lithium-ion (Li-ion) Battery. Because of environmental conditions in Qatar, the best choice for energy storage type seems to be the lead-acid type battery.

6. Power Conditioning Unit

The power conditioning unit combines the electrical energy from the solar and wind power plants which have different characteristics. It should also include a maximum power tracker system to absorb maximum power from solar modules. Using the electrical energy storage, the power conditioning unit will control the power flow in order to provide the load demand in case of variation in the wind blow or sun irradiation. The output of power plant should be at the same voltage and frequency of the grid and using power electronic switching methods like ac/ac converters, this unit will be coupled to the utility grid [33-40]. The power conditioning unit contains four major sections as follows:

6.1 Maximum Power Point Tracker System (MPPT)

MPPTs are controlled power electronic DC to DC converters that ensure that photovoltaic panel or array always deliver maximum available power. It is also important that these devices be efficient, reliable and inexpensive [41,42]. The electrical characteristic of a solar panel is a function of the intensity of solar irradiation and the operation temperature of the solar panel. An increased isolation level and decrease panel temperature result in higher panel power output. Figure 11 and 12 show the output characteristics of a solar array in different insulations of sun light and different temperature. It can be observed that the maximum power point of output power changes by variation of insulation of light and the operating temperature so it is necessary to track this point to deliver the maximum available power to the load [5].

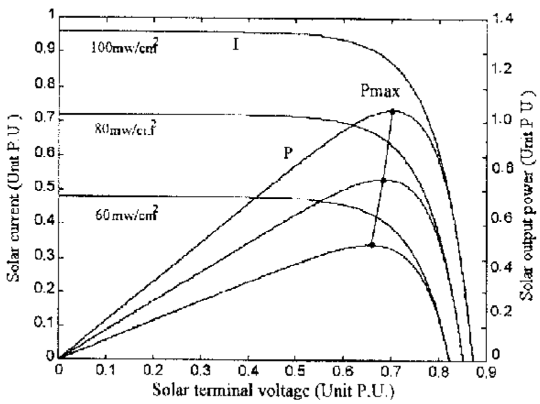

Fig.11 Output characteristics of a typical solar panel for different insulations [2]

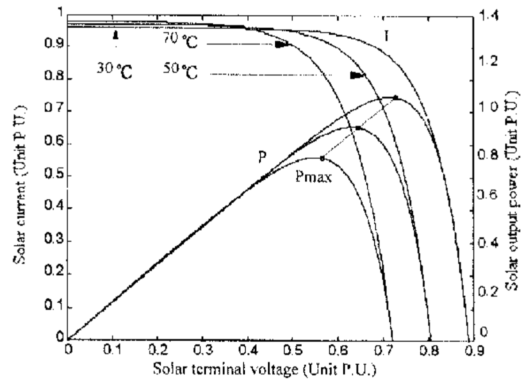

Fig. 12 Output Characteristics of a typical solar panel for different temperatures [2]

6.2 Battery Charge Controller

The charge and discharge of the batteries (the electrical energy storage unit) are based on the control commands sent by the DSP controller in order to guarantee the power quality of the output electric power. The configuration and specification of this controller will be investigated and designed during this work.

6.3 Output Inverter

To provide the electric energy for the commercial or residential loads, the output power should be in the form of AC with specific voltage and frequency. The power conditioning unit will invert the DC electricity to the specific AC form. Also the system should have the ability of injecting reactive power to the output in order to improve the power factor of the network. This feature (in large scale) could help the regional network to work with a better power.

7. Proposed Test Bed for Qatar

Figure 13 shows the proposed test bed in the project during the first two years of the research.

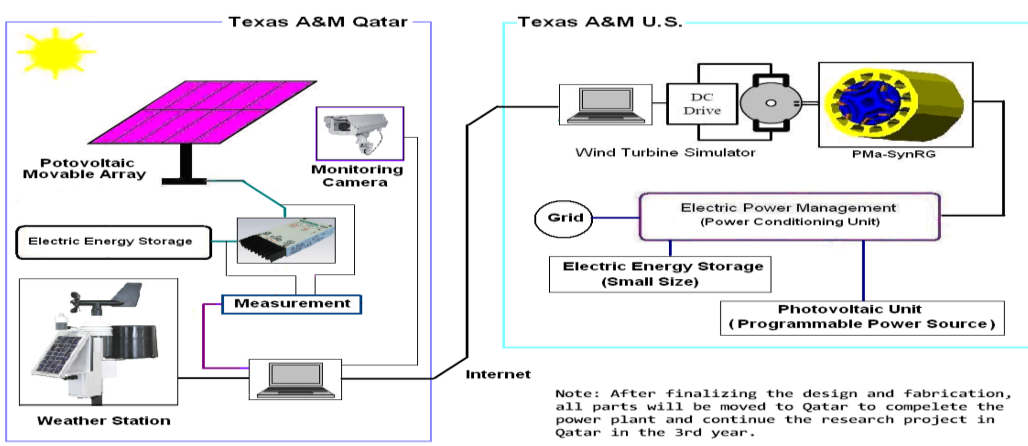

Fig.13. Proposed Test Bed at TAMUQ and TAMUCS for the 1st and 2nd year.

Conclusion

In this paper, a prototype power plant combining solar and wind energies has been investigated. A battery storage system will be used as a backup system and also as a means for generating power continuously without any interruption. The solar power plant includes a 1 kW solar array mounted on a solar tracker system to increase the solar energy absorption. The wind power plant will use a 3 kW permanent magnet-assisted synchronous reluctance machine and a wind turbine simulator used to drive this generator. Since the output characteristic of these systems are not the same, a highly efficient power conditioning system will be designed and implemented to hybridize the energy obtained from the solar power plant and the wind power plant. This system will also use batteries as energy storage to support the hybrid power plant during the variation of the wind and the sun radiation to provide the energy for the load with maximum power quality. In addition, this system will contain the drive system for the PMa-SynRG, maximum power point tracker to absorb maximum power from the photovoltaic array, and the AC converter to provide electricity for the utility grid with specified voltage and frequency. This system will be able to improve the power factor by injecting the reactive power to the network.

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