Monitoring of Photovoltaic Wind-Turbine Battery Hybrid System

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Abstract: - The purpose of the work is to investigate a monitoring of autonomous photovoltaic battery wind turbine hybrid system (PVBWHS). The PV array, wind turbine and the storage batteries sizes are estimated based the site of application; Jazan province, KSA. The sizing result of the proposed PVBWHS is generator with 2.16kW, wind turbine generator with 2kW, Battery Bank with ~400Ah, and 5kW ratings of inverter and hybrid system controller.

In this paper an intelligent graphical user interface (GUI) is built in sub-menus for system characterization. The PVBWHS modeling, simulation, and performance monitoring are also introduced. Models are made to simulate the different power sources; PV system, Wind turbine, a storage battery, the electrical loads, and required meteorological conditions. A LabVIEW model is designed whereby the hybrid system components are simulated as virtual instruments [VI] interacted with functional blocks. The developed monitoring system measures continuously the available power generated from the solar array and wind turbine, and the functional VI compare this with the actual load demand on real time estimates the storage battery operation mode.

Keywords: PV array, wind turbine, sizing, modeling, monitoring system, hybrid system, sensors and actuators, LabVIEW, Virtual Instrumentation.

1. Introduction

Saudi Arabia is a large country with an area of 2.3 million km^2. It is a relatively rich and rapidly developing country and so demand for electricity is growing on average at around 5% annually. Over the next 25 years, it is estimated that US$117 billion will be invested in the country's power sector. The state power grid system has supplied electricity to approximately 80% of the population living in the state capitals and industrial centers. It is highly uneconomical to extend the electrical power grid system into the sparsely populated regions of the Kingdom.

Hence there are many small remote communities that need an independent source of electrical energy. These locations represent a significant potential for renewable energy applications. The importance of using renewable energy in Saudi Arabia will not only be confined to meeting the demands of remote sites, but can also contribute to the national grid, helping to meet the peak-load demand during the summer months.

Even though Saudi Arabia is a leading oil producer, it is keenly interested in taking an active part in the development of new technologies for exploiting and utilizing renewable sources of energy. The most natural renewable energy sources which are freely available are wind and solar. The power in the earth's wind and in the solar radiation, which reaches the earth, is sufficient to make significant as well as strategic contributions to the Kingdom energy supply.

Due to the fluctuating power supplies of the renewable energy sources and the natural varying of the load demands, the hybrid systems that composes a multiple renewable energy sources is preferred compared to standalone's. The proposed hybrid system is comprised of PV, storage battery and wind turbine generator. The combined utilization of these renewable energy sources are therefore becoming increasingly attractive and are being widely used as alternative of oil-produced energy. Economic aspects of these renewable energy technologies are sufficiently promising to include them for rising power generation capability in developing countries. These hybrid energy systems are becoming popular in remote area power generation applications due to advancements in renewable energy technologies and substantial rise in prices of petroleum products. Research and development efforts in solar, wind, and other renewable energy technologies are required to continue for, improving their performance, establishing techniques for accurately predicting their output and reliably monitoring and control its operation performance.

The most frequently used hybrid system is the hybrid which consists of Photovoltaic (PV) modules and wind turbines. Because the supply pattern of different renewable energy sources intermittent but with different patterns of intermittency, it is often possible to achieve a better overall supply pattern by integrating two or more sources [4-7, 11, 18, 21-23].

Optimum match design is very important for PV/wind hybrid system, which can guarantee battery bank working at the optimum conditions as possible as can be, therefore the battery bank's lifetime can be prolonged to the maximum and energy production cost decreased to the minimum.

The main advantages of a hybrid system can be summarized as:

- The possibility to combine two or more renewable energy sources, based on the natural local potential of the users.
- Environmental friendly especially in terms of CO_2 emissions reduction.
- Low cost – wind energy, and also solar energy can be competitive with oil, nuclear, coal and gas energy.
- Diversity and security of supply.
- Rapid deployment - modular and quick to install.
- Fuel is abundant, free and inexhaustible.
- Costs are predictable and not influenced by fuel price fluctuations although fluctuations in the price of batteries will be an influence where these are incorporated.

2. Block Diagram of a Hybrid System

There are many possible configurations of hybrid power systems. One way to classify systems architectures is to distinguish between AC and DC bus systems. Figure 1illustrates the block diagram of this configuration.

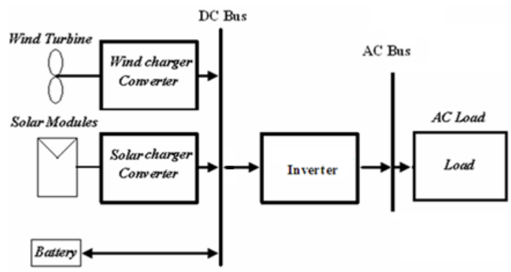

Figure 1, Block Diagram of Photovoltaic Wind Turbine and Storage Battery Hybrid System

DC bus systems are those where the renewable energy components and sometimes even the backup diesel generator feed their power to a DC bus, to which is connected an inverter that supplies the loads. This is for small hybrid systems, as shown in Figure 2. Large power hybrid systems use an AC bus architecture where wind turbines are connected to the AC distribution bus and can serve the loads directly. The configuration used to be evaluated in this thesis has a DC bus which combines the DC output of the PV module, the DC output of the wind turbine, and the battery bank.

The AC bus of this configuration combines the output of the bidirectional inverter, the output of the back-up diesel generator and the load. This parallel configuration requires no switching of the AC load supply while maintaining flexibility of energy source, but the bidirectional power inverter shall be chosen to deal with this mode of operation.

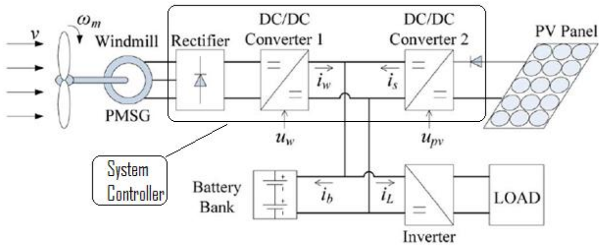

Figure 2, Wiring Diagram of PVWBH System [14]

3. Meteorological Data Base Modeling (MDB)

The site of application weather conditions affects directly the performance of system. Solar radiation affects the generated current value as a major parameter while its affects on solar array voltage is minor. The temperature has a vice versa affects on solar array current and voltage with respect to solar radiation. The wind speed and wind direction affects strongly the output power from wind turbine both as major parameters [3, 26].

3.1. Solar Radiation Modeling

A solar radiation sub-program is built on the LabVIEW GUI and Math-script to calculate the daily average global solar radiation on horizontal and tilted surfaces of solar array.

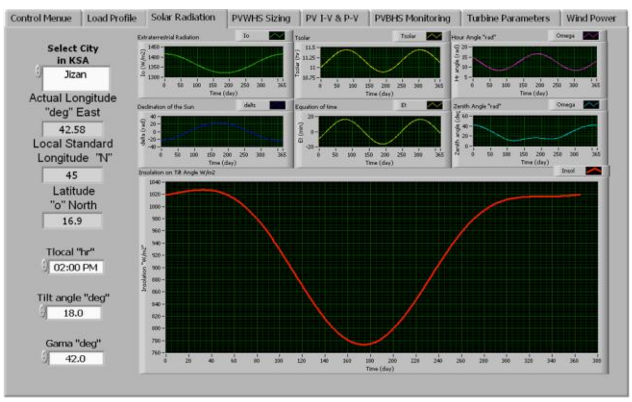

Figure 3, GUI of Solar Radiation at extraterrestrial and on tilt angle of the site of application

The extraterrestrial radiation based on the mean Sun-Earth distance, zenith, azimuth, hour angle, solar and local standard time, equation of time and sunrise and sunset hours; all these parameters needed calculating the horizontal and tilted solar radiation are modeled and values are dynamically calculated and presented in this paper as shown in Figure 3 [5]. In the following two figures; Figure 4 and Figure 5, the details of solar radiation calculation parameters at noon are illustrated.

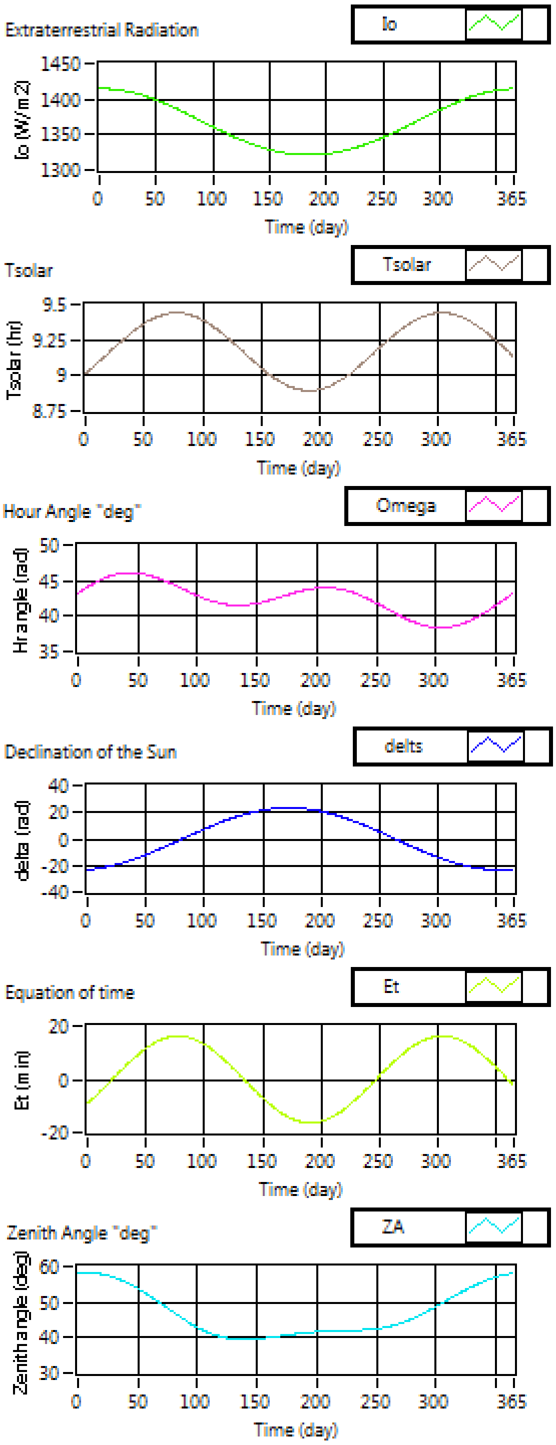

Figure 4, Parameters of Solar Radiation Estimation

In the GUI model of solar radiation it could be noted that, data base of multiple sites of applications in Kingdom Saudi Arabia is added. The control panel has the capability to estimate the different parameters of solar radiation at any local time, any tilt and azimuth angles.

The following figure represents a solar radiation at Jazan Provence (JP) at noon.

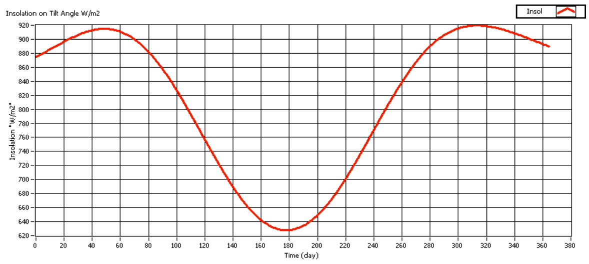
Figure 5, Average daily Solar Radiation at JP at noon.

The following three figures confirm the results taken from the developed software models.

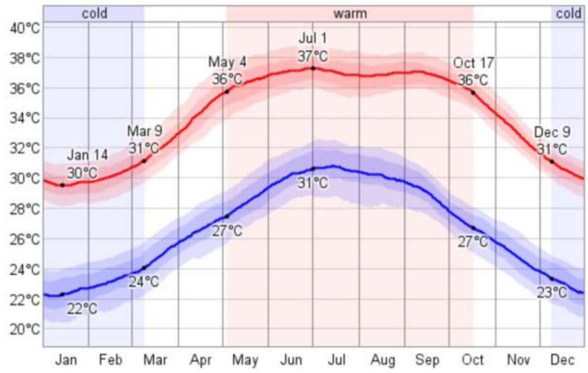

Figure 6, Daily High and Low Temperature

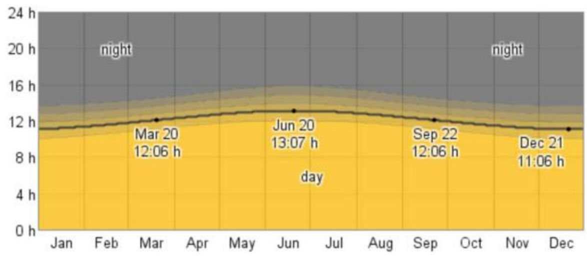

Figure 7, Daily Hours of Daylight and Twilight

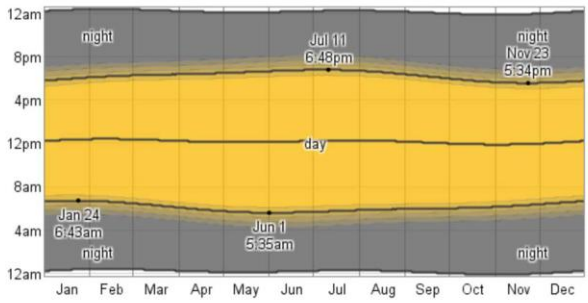

Figure 8, Daily Sunrise & Sunset with Twilight

4. Wing Energy Meteorological data

The site of application values of wind speed and wind direction are taken from an approved ATLAS of JP. The average minimum and maximum wind speed lies between 3 and 8 m/s, this means that the wind turbine will be in operation and generate sensible values of output power during all the day. The following two figures show the wind speed and wind direction of JP.

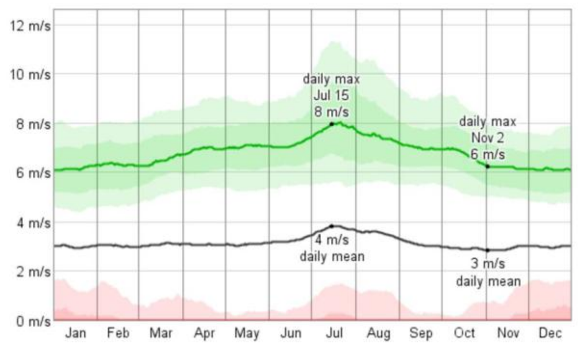

Figure 9, Wind Speed of JP

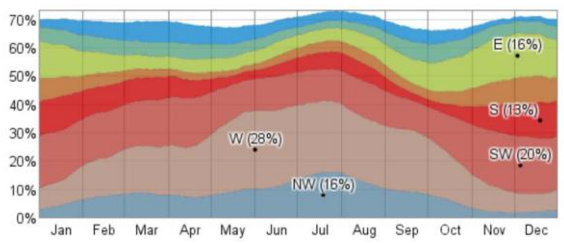

Figure 10, Fraction of Time Spent with Various Wind Directions of JP

5. GUI of PVBWHS Main Control Page

The main front panel page in the developed GUI is introduced in Figure 12. The page contains all the launching buttons of the other GUI pages. It also contains in the middle the toggle switch between “Emulation” or “Hardware”, and the wind speed control bar. In the right side it contains the solar radiation control knob, the read data buffers from data acquisition boards. In the left side, the rotor speed of wind turbine and the wind direction control are allocated. In the bottom of page, the serial interface parameters; lime com port number, baud rate, read buffer, etc are present [2, 8-9, 13-15, 20].

6. PVBWHS Components Sizing

The specific output power from the solar array (SA) depends on the type of solar array (SA), MDB parameters, site parameters type, and inclination of SA. The orientation of the solar arrays strongly affects the generated output power [1, 10, 12, 16-17, 24-25]. The energy transfer from the solar array to batteries and loads is shown in Figure 11.

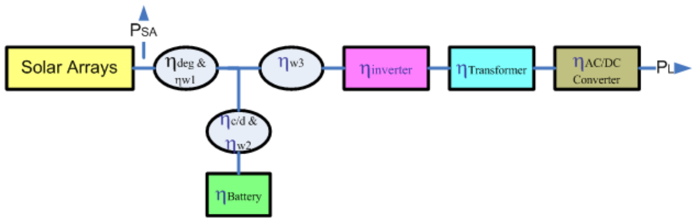

Figure 11, Energy Transfer Diagram of PV Battery System

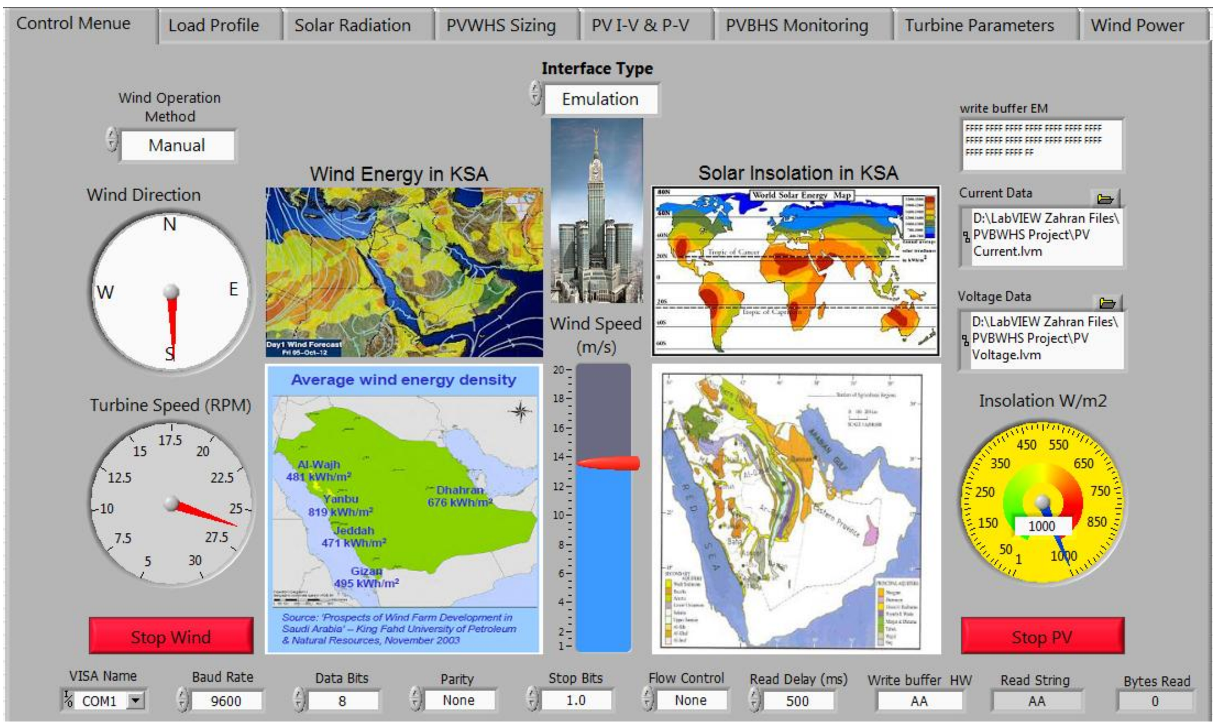

Figure 12, the main Control Page Front panel

The PVBWHS load profile, load types is shown in Figure 13.

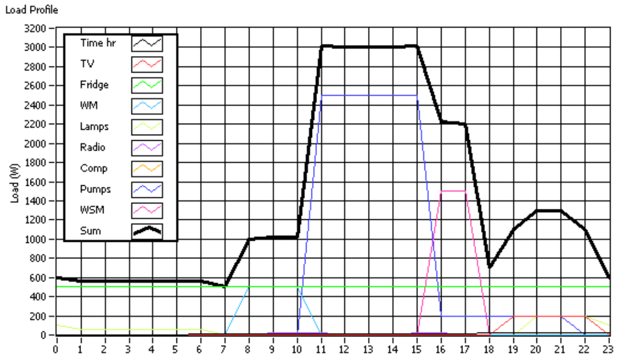

Figure 13, Load Profile

From the energy balance point of view, the amount of average power that must be produced by the solar arrays, Psa could be expressed as:

$$P_{sa}=\{(P_e*T_e/X_e)+(P_d*T_d/X_d)\}/T_d \qquad (1)$$

Where:

Pe, Pd is the power requirements during eclipse and daylight (power budget),

Xe, Xd is the efficiency of the paths from the arrays to the batteries and the loads, and

Te, Td is the times in eclipse and daylight.

The specific output power from solar arrays at the terminals could be expressed as follows:

$$P_{SA}(W/m^2)=$$
$$P_n*FF*K_{ill}*K_{th}*K_{mppd}*\eta_{sys}*K_d \qquad (2)$$

Where:

P_n is the output power at begins of life;

P_n = AM1.5 (W/m^2) * η_{SA} (~ 0.14),

FF is the filling factor of SA module; ~0.85,

K_{ill} is the solar array surface illumination coefficient,

K_{th} is the thermal coefficient of solar array,

K_{mppd} is the matching factor between SA MPP,

η_{sys} is the energy transmission efficiency; ~0.87,

K_d is the Si solar array degradation parameter; ~ 0.9

By estimating the specific output power from solar arrays and substitution to Eq. 3, we get the results of Psa, the required area of solar arrays can be estimated.

$$Area = Psa / P_{SA} \qquad (3)$$

A sizing sub-program is built in the GUI of LabVIEW, the system parameters are given and the sizing results have been got. The sizing menu is shown in Figure 14 .

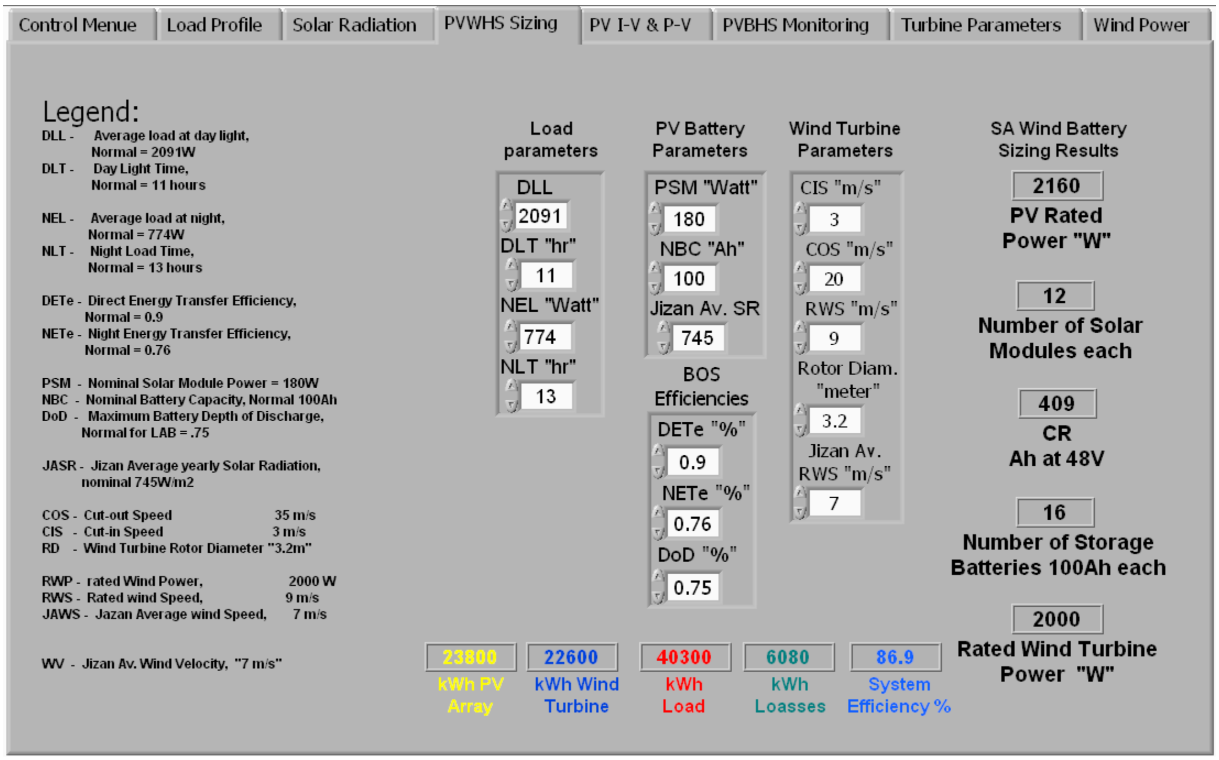

Figure 14, PVBWHS Sizing parameters and results Menu

7. BWHS Components Modeling

The PV array model as well as the dynamic wind turbine model is presented in the following two sections:

7.1. Modeling of the Solar Array

The sized solar array is modeled. The I_V and P_V curves are shown in Figure 15. The values of open circuit voltage and short circuit current are shown on graph while current, voltage and out power at maximum power point is illustrated. It should be noted that the solar array characteristics and dynamically changed either with solar radiation or temperature changes.

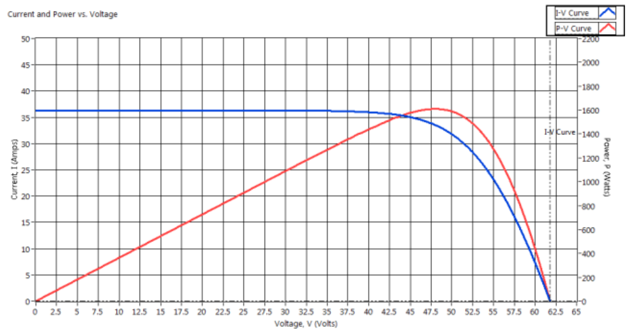

Figure 15, V-I and V-P Curves of the solar array at Jazan Average Solar Radiation, 745 W/m2

7.2. Dynamic Modeling of the Wind Turbine

The wind turbine is characterized by no dimensional curves of the power coefficient (Cp) as a function of both the tip speed ratio (λ) and the blade pitch angle (β). In order to fully utilize the available wind energy, the value of (λ) should be maintained at its optimum value. Therefore, the power coefficient corresponding to that value will become maximum also.

The model is based on the steady-state power characteristics of the turbine. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine must be combined with those of the generator coupled to the turbine [27].

The tip speed ratio (λ) can be defined as the ratio of the angular rotor speed of the wind turbine to the linear wind speed at the tip of the blades. It can be expressed as follows:

$$\lambda = \omega_t R / V_\omega \qquad (4)$$

Where

- R is the wind turbine rotor radius,
- Vω is the wind speed and ωt is the mechanical angular rotor speed of the wind turbine.

A generic equation is used to model $C_p(\lambda,\beta)$. This equation, based on the modeling turbine characteristics of [27], is:

$$C_p(\lambda,\beta) = C_1 * \left(C_2/\lambda_i - C_3*\beta - C_4\right) * e^{(-C_5/\lambda_i)} + C_6*\lambda \qquad (5)$$

Where the coefficients $c1$ to $c6$ are:

- $c1 = 0.5176$, $c2 = 116$, $c3 = 0.4$,
- $c4 = 5$, $c5 = 21$ and $c6 = 0.0068$.

In addition to Eq. 5, the relation between λ and β can be found in the following relation [27]:

$$1/\lambda_i = \frac{1}{\lambda + 0.08*\beta} - \frac{0.035}{\beta^3 + 1} \qquad (6)$$

The $C_{p\text{-}\lambda}$ characteristics, for different values of the pitch angle β, are illustrated below. The maximum value of C_p ($C_{pmax} = 0.48$) is achieved for β = 0 degree and for λ = 8.1. This particular value of λ is defined as the nominal value (λ_nom).

The instantaneous values of Cp as a function of rotor speed and angle of attack is shown in Figure 17.

Wind turbine is designed to have low cut-in and cut-out speed (2-3m/s: 7-9m/s) to suit Jazan wind condition.

The power output equation [14] of wind turbine can be described in Eq. 8:

$$P_t = \tfrac{1}{2}\rho\pi C_p V^3(\lambda,\beta) R^2 \qquad (7)$$

Where: P_T = wind power (W)
ρ = air density (kg/m3)
V = wind speed (m/s)
R = radius of turbine blades (m2)
C_P = wind power coefficient.

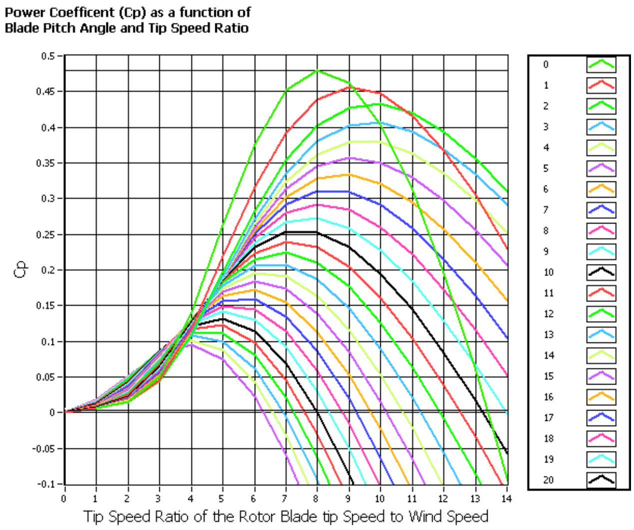

Figure 16, Wind turbine $C_{p\text{-}\lambda}$ characteristics

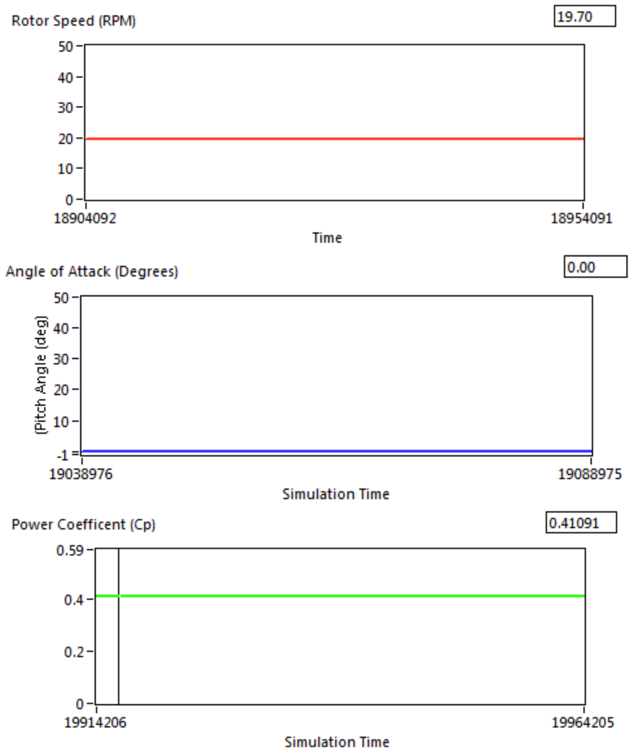

Figure 17, Wind Turbine efficiency Parameters Cp

The relation between the wind turbine output power and the wind speeds is shown in Figure 18. The cut-in speed is 3m/s, rated speed is 9m/s while cut-out speed is 20m/s.

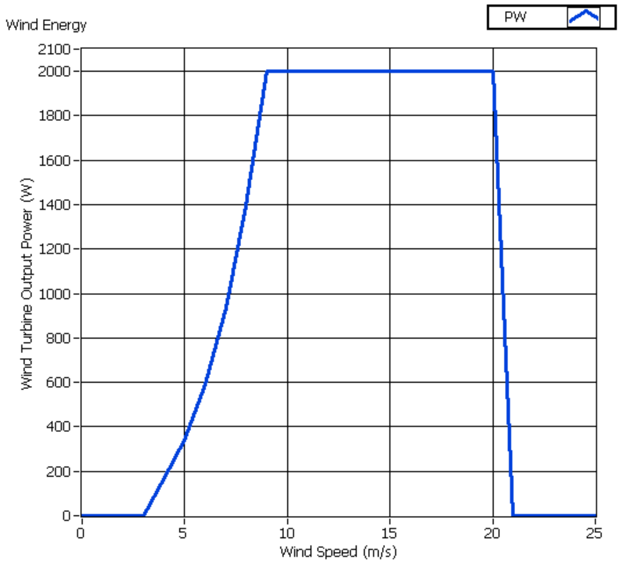

Figure 18, Wind turbine Power - Wind speed curve

In case when wind speed is greater than rated speed, it should be noted that the power in wind is greater than output power from wind turbine, as shown in Figure 19.

8. LabVIEW based System Hardware Emulation and Monitoring

In this section, the block diagram and the different from panel control and monitoring pages will be presented.

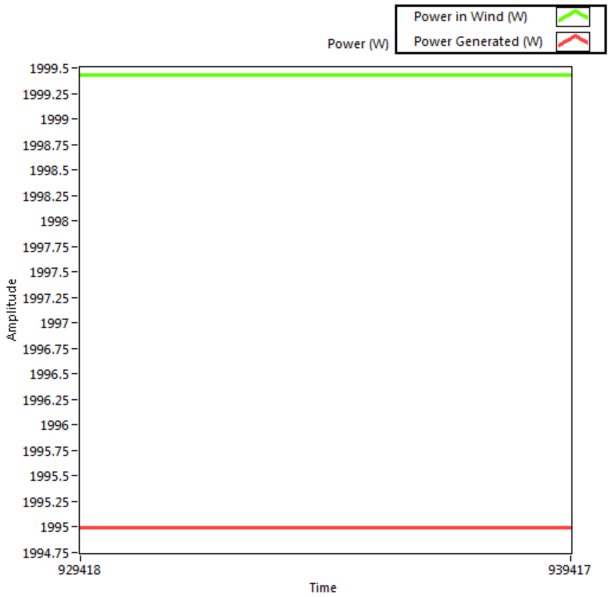

Figure 19, Power in Wind and Generated Power

8.1. Implemented Block Diagram

The implemented LabVIEW block diagram is developed in two cases; the first case is hardware interfacing with physical components and data acquisition module through serial interfacing. The second case depends on modeling and emulation of the PVBWHS components variables.

9. GUI of PVBWHS Monitoring Page

The photovoltaic battery wind turbine hybrid system monitoring page is shown in Figure 20. The wiring diagram of hybrid system, number of solar array strings, control switches, and load branches controls are illustrated. The current values of PV, wind, Battery and summation load currents are also presented. The instantaneous values of system variables are dynamically changes according to input variables like; solar radiation, wind speeds and temperature. The summation output power of hybrid system as well as status of battery operation charging or discharging is illustrated on the hybrid system monitoring GUI too. The imaged stated in the main front panel presents the daily average and distributed renewable energy resources in the Kingdom Saudi Arabia in general and for JP especially.

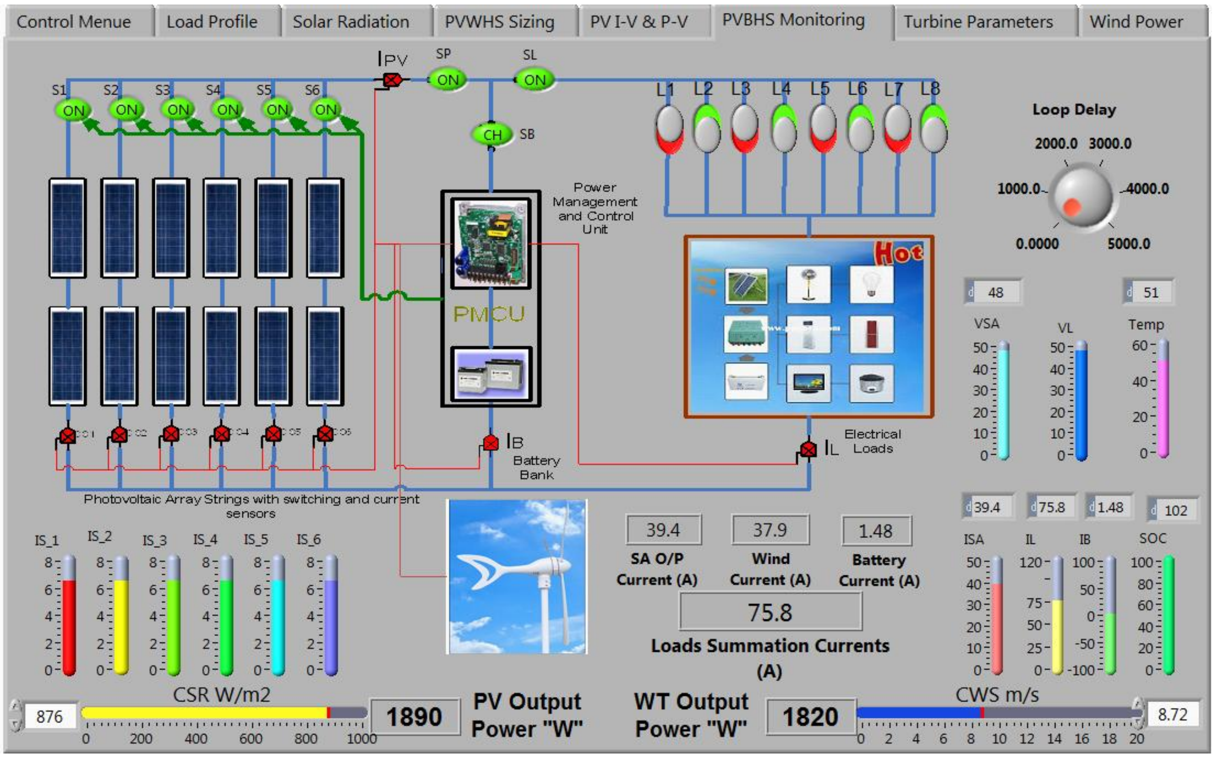

Figure 20, PVBWHS system performance study showing all the necessary variables

10. Conclusions:

The system was created in LabVIEW environment, as it provides a programming language with possibilities of easy control of external hardware and of being used in many hardware and software platforms with a variety of operating systems. The created system was implemented on a PC and Windows Operating System.

In the developed program, eight interacted menus have been implemented; main control menu, load profile menu, solar radiation menu, sizing menu, PV characteristics menu, hybrid system monitoring menu, wind turbine parameters menu and wind and wind turbine power menu. The different menus are working in active mode by means any change in design or MDB parameters will directly affect the system sizing or system output energy performance. The system design parameters in this paper is introduced for a specific site of application; Jazan Provence KSA where the hybrid system is installed, but the developed program could be applied at any site and any load profile worldwide.

The developed monitoring system has the capability to work in emulation mode or hardware interfacing mode. In emulation mode, the signals and actuators are emulated by potentiometers and electronic switches while in hardware interfacing mode, a microcontroller with analog multiplexer working as data acquisition is interfaced with PC with LabVIEW monitoring and management program.

11. Acknowledgment

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