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A Comprehensive Study on PV/BS/UG Hybrid Energy System: "Case study on Saudi Arabia"

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Abstract— In this paper we introduce a fully automated power management control system for hybrid PV/Battery Sank/ Utility Grid (PV/B S/UG) system. Different tilt angles have been tested to specify the best tilt angle for the selected site. The generated power from the PV system is measured and compared with the calculated one. The deficit and surplus power have been determined. The power management technique is designed in different operating modes and controlled using a programmed Arduino controller. A full algorithm as well as complete program using C++ have been designed and applied to manage the power flow supplied from the three available sources through the Arduino Nano controller. The introduced system is tested using a real lighting load of University of Business and Technology located in Dhahban-Jeddah, Saudi Arabia. A fuzzy logic design is used to verify the proposed power management system during the day. This methodology uses the hourly radiation, and hourly load power measured at different title angles of PV system. Very valuable results can be extracted from the proposed technique that could help researchers and decision makers. The results obtained from the proposed system have established the economic feasibility of installing hybrid energy systems in many sites of Saudi Arabia.

***Index Terms*— Hybrid System, Photovoltaic (PV), Battery Storage (BS), Utility Grid (UG), Tilt angle.**

I. INTRODUCTION

Solar energy is considered as a main future source of clean and cheap energy because; it is a clean, unfailing and environment-friendly potential resource among all renewable energy options [1]. Saudi Arabia has continuous supply of solar energy during a whole year however; due to seasonal and periodic variations of solar energy photovoltaic system needs a battery bank to store the extra energy [2-5].

PV systems have two major problems; it has a very low conversion efficiency of electric power generation about 10-24% [6], and it is reduced under low irradiation conditions. PV panels have a nonlinear voltage-current characteristic [7] due to the variation of maximum power point (MPP), which depends on the environmental factors, such as irradiation and temperature [8]. To generate a maximum power from PV solar panels, we need a sun tracking system that follows the sun. Automatic solar tracking system using Arduino hardware system design is used for continuously tacking the sun to obtain the maximum power point [9]. Arduino is an open source electronic prototype platform that consists of 8-bit Atmel AVR microcontroller such as Atmega328. In this paper, we obtain the maximum power point using Arduino programming system design.

Power management for any hybrid system is considered as a key role to maximize the system performance [10]. In this paper, a power management of the proposed hybrid PV/BB/UG system given in [11] is controlled by an Arduino system.

II. PROPOSED SYSTEM MODELLING

A. PV System Model

The tilt angle of the PV system in accordance with the movement of the sun determines the intensity of the sunlight falling on the modules surface and, therefore, it will affect the system output power. Due to the Saudi Arabia location at north of the equator, the solar panel is installed facing south. The PV array surface should be positioned directly perpendicular to the sun's rays. This tilt angle of the solar panel has a great effect on the amount of solar radiation will capture and then on the amount of sunlight to be converted into electricity.

The tilt angle of the designed system has been changed to examine the best tilt angle of the selected site. This can be easily achieved using a servo motor coupled on the solar panel system shaft and various readings have been done on the optimum tilt and orientation angle for fixed surfaces.

Therefore, the optimum tilt angle provides maximum power output from the system during the month. The tilt angle can be fixed at a certain angle all year round, seasonally, or monthly changed. In this paper, the PV array is tested at different tilt angle and the PV generated power is measure and then the actual load sharing is calculated and compared with the theoretical results obtained by the Authors [11].

Theoretical calculations were performed to determine total generated power at a given tilt angle.

Generated power calculation:

The average generated power has been estimated hourly, monthly and yearly using Equation (1) [11]:

$$P_h = A_{effy} \times H_{th} \times \eta_o \times \eta_t \times \eta_{pc} \times {}^{V_f}\!/_{F_s} \quad (1)$$

where $A_{eff}\,y$ is effective solar cell area yearly, H_{th} is hourly radiation on the tilted surface (kW/m2), $\eta_o$is the operating efficiency of the cell, η_t is the transformer efficiency, η_{pc} is the power condition unit efficiency, V_f is the variability factor, and F_s is the safety factor for inaccuracy of the insulation data.

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$A_{eff}\,y$ is effective solar cell area yearly can be calculated using the following Equation (2)[11]:

$$A_{eff}y = \sum_{i-1}^{12}\sum_{t=6.5}^{18.5}\frac{A_{eff}h}{12\times 8} \quad (2)$$

And $A_{eff}\,h$ can be calculated from Equation (3):

$$A_{eff}h = (P_L \times F_s)/(H_{th}\times \eta_o \times \eta_t \times \eta_{pc} \times V_f) \quad (3)$$

$$\eta_o = \eta_r(1 - 0.0062(T_c - T_r) \quad (4)$$

And Tc can be calculated using Equation (5).

$$T_c = T_r + K_l \times H_{th} \times 100 \quad (5)$$

Tc and T_r are the operating and reference temperatures respectively, Kl is monthly average of daily clearness index, and η_r is the reference efficiency.

Hence, the generated power per day and per year is calculated as follow:

$$P_d = \sum_{t=6.5}^{18.5}\frac{P_h}{13} \quad (6)$$

$$P_y = \sum_{i=1}^{12}\frac{P_d}{12} \quad (7)$$

The following Figure (1) illustrates the schematic diagram of the designed system. The connection diagram of the system components and the wiring system is as shown in this figure.

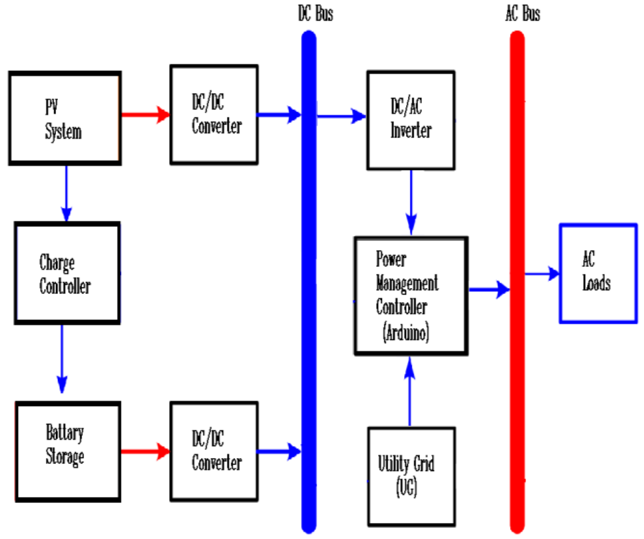

Fig 1: Block diagram of the proposed hybrid system.

According to our model, the power flow management will be using Arduino Nano program. In case of the $P_{PV} > P_L$, the solar panel will connected directly to the load and the battery will charge. In case of $P_{PV}+P_{BB} > P_L$, hence, the PV panels and battery bank will charge the load. In last condition, the $P_{PV}+P_{BB} < P_L$, the utility grid will connected to the load and battery will be charged from the UG. The control unit is controlled by Arduino Nano program.

In this model, we used a small solar panel and servo motor, for testing the value of MPP which are powered by original solar panels, so the overall drawn power is very low. The first part of the Arduino C++ program is responsible for determining the position of the maximum voltage. The PV solar panels are positioned to the new measured angle by Arduino using a servo motor.

B. Battery Storage Model

The energy balance between the PV energy systems and the load; the battery state of charge, SOC, after certain period of time, can be calculated from the following equations for charging and discharging consequently as illustrated in Wqns. (8,9) [13].

$$E_B(t+1) = E_B(t)(1\text{-}\sigma) + \text{surplus power}^* \eta_{BC} \quad (8)$$

$$E_B(t+1) = E_B(t)(1\text{-}\sigma) - \text{deficit power}/\ \eta_{BD} \quad (9)$$

Where σ is the hourly self-discharge rate; the manufacturer documentation recommended its value of 0.2% per day for most batteries [13]. (Yang et al., 2008), η_{BC} and η_{BC} are the charging and discharging efficiency of the battery and it is considered 90% and 85%, respectively [14].

C. Arduino Controller Model

The designed and embedded algorithm on Arduino Nano controller is based on the comparison between the output power from PV module at the given tilt angle and decide which switches to turn on and which to turns off based on the input load data. The following Figure 2 illustrate the Arduino Nano mechanism,

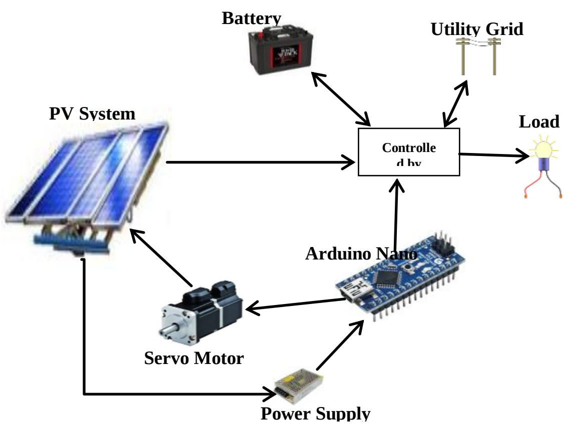

Fig 2: Block diagram of the proposed control system using Arduino Nano

The different possible operation modes are cleared in the following Figure 3. The decision taken by the controller is based mainly which power sources combination is sufficient to supply the load power demand. The proposed four different modules introduced in [11] are considered in our program. The given models are as shown in Figure 3.

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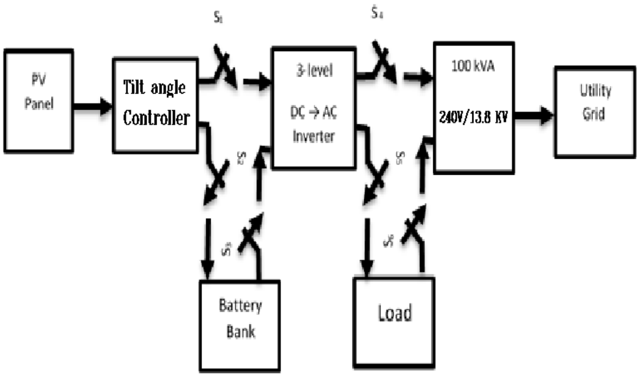

Fig 3: Block diagram of the proposed supply management algorithm.

The following are the four operating modes logic that has been implemented:

Mode 1:

In case of $P_{PV} > P_L$ and P_{BB} is not full, the PV output power will feed the load and charge the battery.

Mode 2:

In case of $P_{PV} > P_L$ and P_{BB} is full, The PV output power will feed the load and feed the utility grid as well.

Mode 3:

In case of $P_{PV}+P_{BB} > P_L$, The PV output power and the battery power will feed the load and the remaining power will feed the utility grid.

Mode 4:

In case of $P_{PV}+P_{BB} < P_L$, The PV output power, battery and the utility grid will feed the load.

The results obtained from the theoretical study done by the authors [11], is illustrated in the following Pie chart, Figure 4. This chart shows the load sharing ratio between the different available sources.

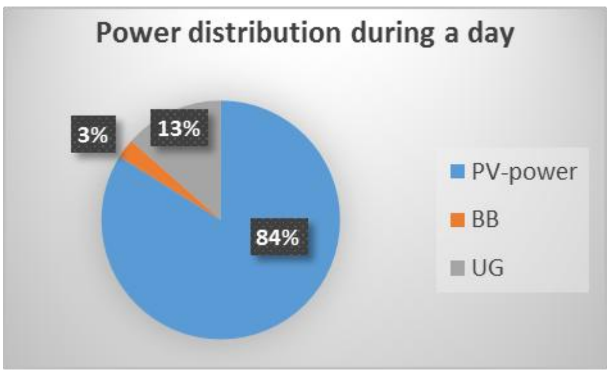

Fig 4: Estimated load sharing during a day(theoretical study)[11].

III. SYSTEM INSTALLATION

An actual solar radiation per hour in Jeddah site is given in [11]. In this paper, we used different tilt angle to measure the generated power according to its position using a sun tracking system.

The proposed system which consists of 12 PV panels connected in series is installed on the Collage of Engineering and Information Technology (CEIT) building. Different tilt angles are considered such as 0^0, 45^0, 65^0, 90^0, 115^0, and 180^0 are illustrated in Figure 5. It is manually adjustable system at this time; however we developed a fully controlled automatically.

(a)

(b)

(c)

(d)

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 6, Issue 7, January 2017

(e)

(f)

Figure 5: Solar panels installed on the roof of CEIT at UBT, Dhahban, KSA at tilt angles (a) tilt angle is 0^0, (b) tilt angle is 45^0, (c) tilt angle is 65^0, (d) tilt angle is 90^0, (e) tilt angle is 115^0, (f) tilt angle is 180^0.

IV. RESULTS AND DISCUSSION

In this paper, we designed and installed a hybrid PV and battery storage system connected to the utility grid to feed a 3 kW load in CEIT, UBT lab. The control system uses an Arduino Nano to control the power management via switching system to switch between BS, PV and UG to feed the load. The load is 3 kVA which is located in the CEIT lab and the load demand is illustrated in Figure 6 as load power starting from 9:00 am to 7:00 pm (working hours of the UBT) and remains at 300 W from 7:00 pm to 9:00 am (not working hours).

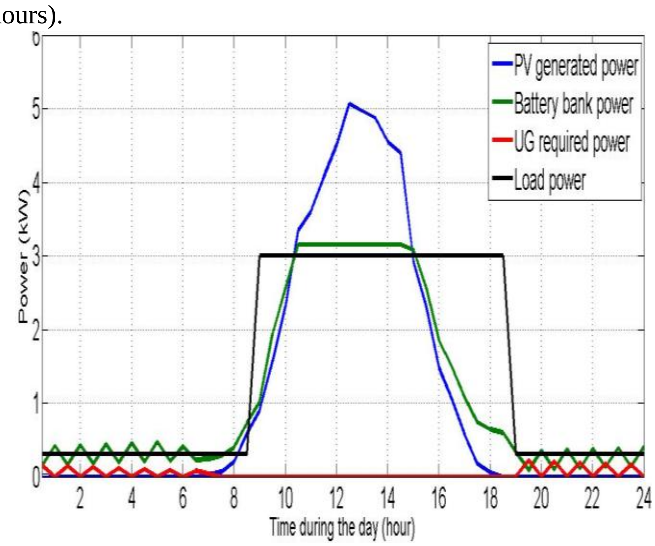

Fig 6: Load power, generated power from PV, storage battery bank power, and UG required power during the day

As clearly shown from Figure 6 and during the night, from 7:00 pm to 9:00 am, the load is 300 VA which is covered from the UG and the battery. PV panels has no generation and the UG charge the battery storage and feed the load, when the battery can supply the power to the load, the UG is disconnected as shown in Red and Green curves in Figure 6. After 10:00 am, the battery is charged and the solar panels generate a higher power than demand power. On the other hand, when the PV power decreased, the UG will feed the load by 7:00 pm and the battery will follow the cycle again.

In Figure 7, the sharing ratio of each power source is given. About 82% of the demand power is produced from PV solar panels, 12% of the needed power feed from the UG power supply, and the battery bank shares by 6% of the demand power. As noted from this figure, the practical sharing ratio is very close to that obtained from the theoretical study as cleared in Figure 4.

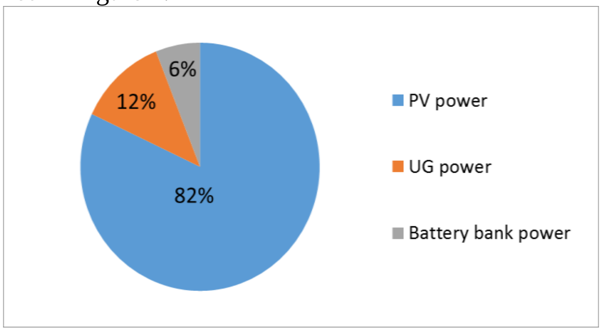

Fig 7: Estimated load sharing during a day(theoretical study)

To enhance our system, we simulate the installed system using Fuzzy logic installed in MATLAB as illustrated in Figure 5. Rules viewer of power management during the day is given in Figure 8.

There are three inputs: PV system, battery banks, and utility grid to receive output power which represents the load demand.

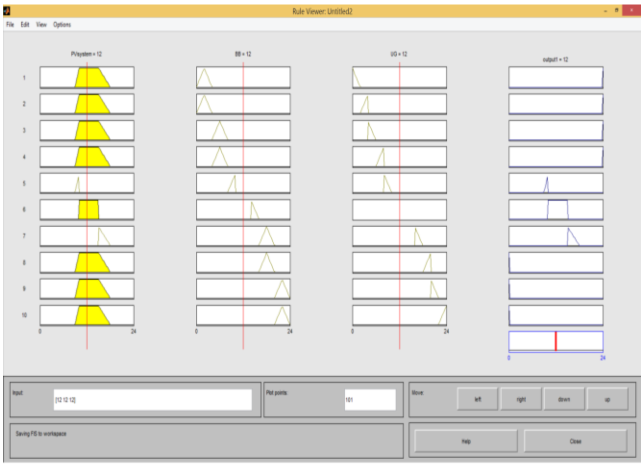

Fig 8: Power management of the installed system using a Fuzzy logic.

In this work we measure the short circuit current, I_{sc}, load current, I_{load}, open circuit voltage, V_{oc}, load voltage, V_{load}, and generated power, P_G at different tilt angles, , 45^0, 65^0, 90^0, 115^0, and 180^0 for a load 3 kW/h.

Figure 9 shows the short circuit current for different tilt angles. In the morning, short circuit currents for all tilt angles are low values then gradually increasing for a maximum value by 12:00 pm and then decreases again with time. A maximum value of the short circuit current is obtained at 12:00 pm for a tilt angle 45^0 is 8.6 A, however the average maximum current is obtained at tilt angle 65^0 during the day. At the tilt angle 180^0, the measured short circuit current is the minimum where the sun light is reflected from the ground in to PV panels.

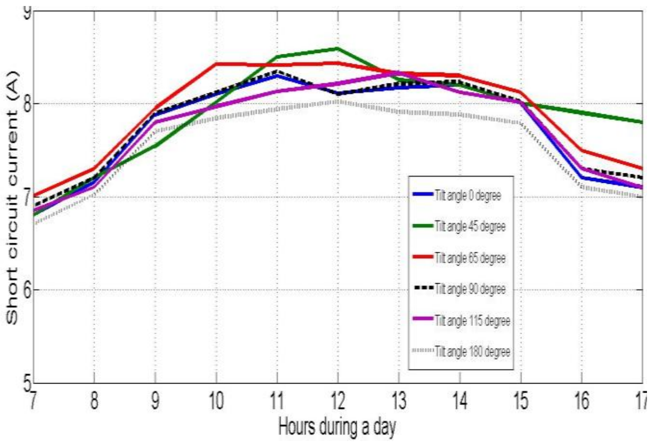

Fig 9: Short circuit current during a day for different tilt angles.

The mesured load current during a day for different tilt angles is illustraed in Figure 10. The maximum value of the current is 8.3 A at 3:00 pm for tilt angle 65^0.

The load current is reduced to to the conection of 3 kW load. At 12:00 pm the load current is around 7.5 A instead of 8.3 A for the short circuit current.

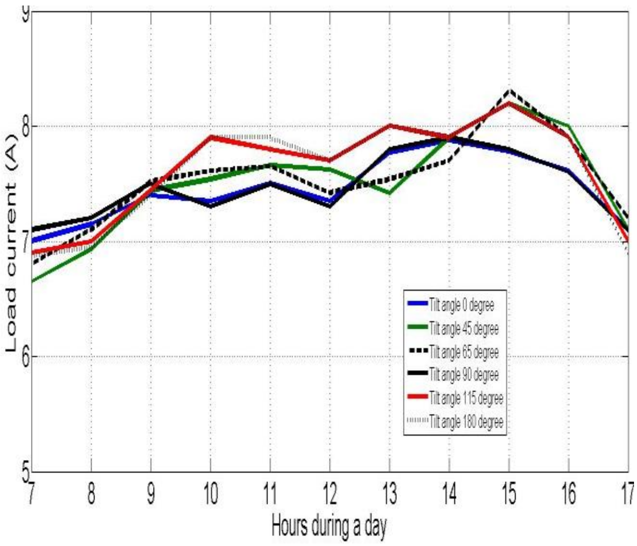

Fig 10: Load current during a day for different tilt angles.

On the other hand, the open circuit voltage during a day is given in Figure 11 at different tilt angles. The peaks are obtained at 12:00 pm and the open circuit voltage is a round 420 V. The best average values are measured at tilt angle 90^0 while the minimum value is measured at 1:00 pm at tilt angle 180^0.

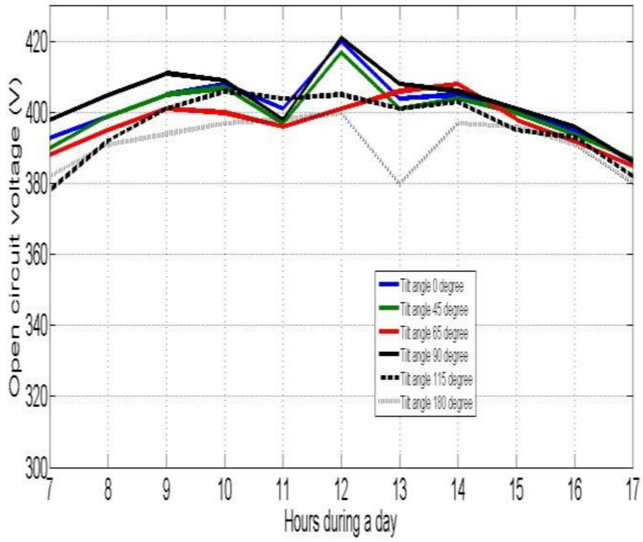

Fig 11: Open circuit voltage during a day for different tilt angles.

Load voltage is measured at different angles during the day for the installed system is given in Figure 12. The maximum voltage is obtained at 12:00 pm at the tilt angles 0^0 and 180^0 and the lowest voltage is obtained at 115^0 of value 315 V. However the most constant value is obtained at tilt angle 65^0.

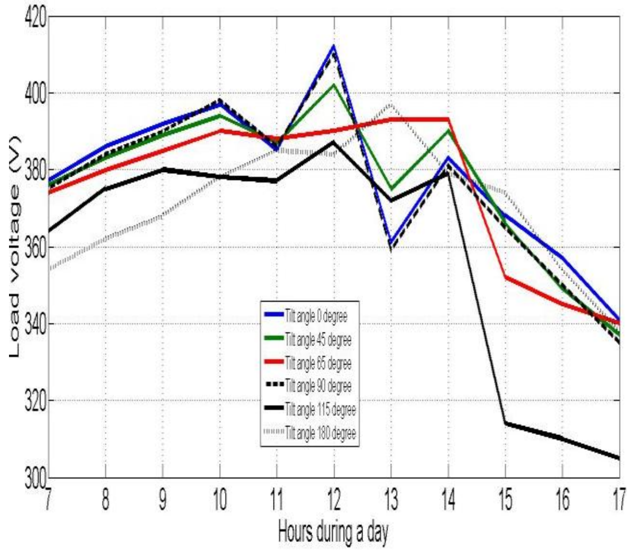

Fig 12: Load voltage during a day for different tilt angles.

In order to measure the performance of the PV panels, we calculate the generated power during the day for different tilt angles as shown in Figure 13. All values are compared to the load power demand, 3 kW. Tilt angles 45^0 and 65^0 are the best tilt angles PV panels which generate the most values power.

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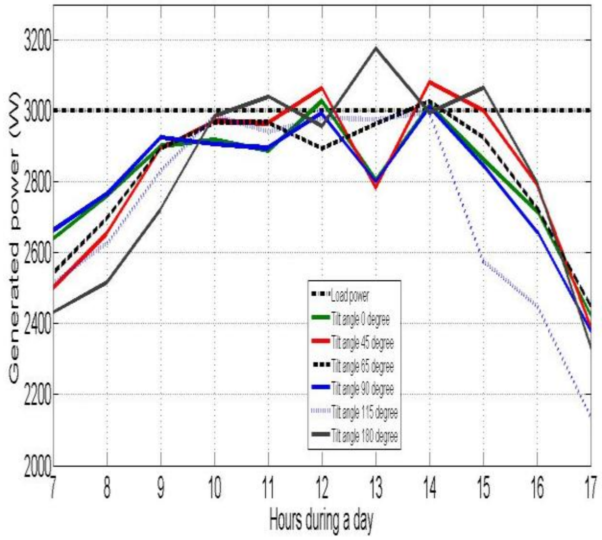

Fig 13: Generated power from PV panels during a day for different tilt angels.

The maximum vales of short circuit current, load current, open circuit voltage, load voltage, and generated power from solar panels are summarized in table 1. As seen from this Table, it can be noticed that the maximum generated power is 3180 watt at 180^o (horizontal position). Also, as shown in this table, the best tilt angle that give the highest power is 45^{st}.

In Table 2, the time at which the maximum values are obtained is illustrated. A maximum short circuit current is 8.6 A obtained at tilt angle 45^0 and at 12:00 pm, while the maximum values of load current is 8.3 A at tilt angle 65^0 and at 3:00 pm. A maximum open circuit voltage is 422 V obtained at tilt angle 90^0 and at 12:00 pm, while the maximum values of load voltage is 414 V at tilt angle 0^0 and at 12:00 pm. The maximum generated power is 3180 W obtained at 180^0 tilt angle and at 1:00 pm.

Table1. Maximum values of short circuit currents, load currents, open circuit voltage, load voltage, and generated power at tilt angels 0^0, 45^0, 65^0, 115^0, and 180^0.

Tilt angle / Maximum Values	0^0	45^0	65^0	90^0	115^0	180^0
Short circuit current (A)	8.3	8.6	8.5	8.3	8.4	8
Load current (A)	7.9	8.2	8.3	7.9	8.2	8.2
Open circuit voltage (V)	420	418	405	422	403	400
Load voltage (V)	414	404	394	413	386	396
Generated power (W)	3040	3090	3020	3005	3000	3180

Table2. Time at the maximum values of short circuit currents, load currents, open circuit voltage, load voltage, and generated power at tilt angels 00, 450, 650, 1150, and 1800.

Tilt angle / Time at maximum	0^0	45^0	65^0	90^0	115^0	180^0
Short circuit current	11:00 am	12:00 pm	10:00 am	11:00 am	1:00 pm	12:00 pm
Load current	2:00 pm	3:00 pm	3:00 pm	2:00 pm	2:00 pm	2:00 pm
Open circuit voltage	12:00 pm	12:00 pm	2:00 pm	12:00 pm	10:00 am	12:00 pm
Load voltage	12:00 pm	12:00 pm	2:00 pm	12:00 pm	12:00 pm	1:00 pm
Generated power	2:00 pm	2:00 pm	2:00 pm	2:00 pm	2:00 pm	1:00 pm

V. CONCLUSION

A hybrid PV/BS/UG system design and implementation has been introduced. The performance of the system is studied for a load of 3 kVA, in UBT University in Jeddah, KSA. The implemented system is a fully automated, where we use different tilt angle algorithm determine the power and consequently the power management technique is controlled using a programmed Arduino Nano chip. We implement the system on the roof of CEIT, UBT and test it using a real lighting load. For different tilt angles, we measure a short circuit current and open circuit voltage of 12 PV panels connected in series at different tilt angles, 0^0, 45^0, 65^0, 90^0, 115^0, and 180^0. A load voltage and current at the same tilt angles are measured and hence the generated power is calculated.

According to our study, PV share by 82% of the power demand, 12% by the utility grid and 6% share by battery bank. The maximum short circuit current 8.6 A obtained at tilt angle 45^0 and at 12:00 pm, while the maximum load current is 8.3 A at tilt angle 65^0 and at 3:00 pm. A maximum open circuit voltage is 422 V obtained at tilt angle 90^0 and at 12:00 pm, while the maximum values of load voltage is 414 V at tilt angle 0^0 and at 12:00 pm. The maximum generated power is 3180 W obtained at 180^0 tilt angle and at 1:00 pm.

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His research interests are in the area of power systems, renewable energy, power electronics, high voltage engineering. where published about 25 papers and number of technical projects. Dr. E. A. El-Sayed has 23 years of teaching experience from 1994 – 2017. I have taught High Voltage, Power System Analysis, power electronics, electric machines, numerical methods.

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