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Optimal Design and Dynamic Modelling of a Hybrid Distributed Generation System Containing Solar PV, Diesel and Wind Turbine with Storage

Demsew Mitiku Teferra

Addis Ababa Science and Technology University

Department of Electrical and Computer Engineering

Addis Ababa, Ethiopia

demsewmitku@gmail.com

Abstract— Due to ever increasing energy consumption, rising public awareness of environmental protection, renewable distributed generation (DG) systems have attracted increased interest. But the intermittent nature of renewable, DGs lead to think about the combination of sources called Hybrid Systems. Hybrid systems are characterized by containing two or more technologies of electrical generation, in order to optimize global efficiency of the processes. Wind and photovoltaic (PV) power generation are two of the most promising renewable energy technologies as duo are complimentary to each other and hence able to provide good and constant supply to meet the rise in demand. The vision of this paper is to show the system controlling and the cost-effective analysis if a transition from conventional to hybrid wind/solar power supply of public and commercial buildings. Case studies of Faji High School electricity demand were carried out.

Keywords: *Hybrid DG system, Renewable Energy, Optimization, Wind Turbine Modeling, PV Modeling, Control Algorism, Charge Controller Modeling, Cost of Energy (COE), Battery Modeling.*

1. INTRODUCTION

Many rural areas of developing countries lack supply of electricity due to poor distribution of grid electricity and financial resources to aid grid extension [1]. The relatively low energy demand in rural areas does not compensate the cost of long-range transmission lines from the national grid. This justifies the use of more decentralized forms of power supply systems which need to be modular in nature and widespread in distribution so that they can be built anywhere near the locations of use. Such power supply systems should be able to provide uninterrupted power supply. Options for providing these include PV, diesel generator sets or a combination of these forms of energy in hybrid system. Wind energy, can be a good power supply option but the problem is that wind speeds are insufficient for power generation in the site. A wind turbine installed in an area with a good wind resource can produce energy cost-effectively, for instance, if wind speed is doubled the system becomes about eight times cheaper [2]. However, the available of wind resource typically varies from season to season; creating a significant variation in the wind turbine output and some areas do not have sufficient wind speeds for power generation thus limiting resource use [3].

Another renewable resource is solar energy which is abundant in nature especially in most developing countries. Solar systems use photovoltaic modules to supply total electric needs. PV systems can be designed for a variety of applications and operational requirements, and can be used for either centralized or distributed power generation. The system is completely independent of traditional energy sources and this energy independence and environmental compatibility are two attractive features of PV systems. The sunlight is free, and no pollution is created from operating PV systems. In general, PV systems that are well designed and properly installed require minimal maintenance and have long service lifetimes [4].The amount of power produced by renewable energy devices such as photovoltaic cells and wind turbines varies significantly on an hourly, daily and seasonal basis due to the variation in the availability of the sun, wind and other renewable resources. This variation means that sometimes power is not available when it is required and on other occasions there is excess power. However, to deliver continuous uninterrupted power supply, the PV array and battery of a standalone solar system have to be excessively over-sized leading to high capital costs.

Another energy supply option for remote areas is the stand-alone diesel generator sets, which are relatively inexpensive to purchase but expensive to operate and maintain [5]. Some generator sets will produce DC electricity for charging batteries directly and AC electricity for running appliances and electrical equipment [6]. Advantages of this option are the low initial capital costs and generation of power on demand. Gensets can be operated with or without a battery but the problem is that if there is no battery they have to be sized for peak power and are therefore less efficient when the load ratio is low? When a genset is designed this way it will operate at partial load for most of its operating life yet specific fuel consumption characteristics of a typical diesel engine show that a diesel generator must be operated above a certain minimum load level in order to maintain efficiency and to reduce the possibility of premature failures [7]. The problem of selecting a diesel generator size for a newly emerging community, or one which has not had continuous power previously, is difficult while population fluctuations, seasonal demand, increase in number and use of electrical appliances are complex issues for designers to assess.

2. Hybrid Micro-grid Power System

The power system considered here is composed of four parts: WT, PV, Generator and battery bank. The two former units generate electricity, in accordance with the local wind and solar energy resources, to supply load; Diesel generator is used to supply load when the output power from wind and PV is not enough to operate this load, as well as to bring the SOC of batteries to an acceptable level. The battery bank forms the energy storage system that can supply the load when there is lack of electricity, and store the surplus power when the power generated exceeds the load.

2.1. Estimating the Output Power of Wind Turbine

The speed of wind is often represented by a random variable. The Weibull distribution function with two parameters is commonly used to describe wind speed data [8, 9]. It provides a convenient representation of the wind speed data for wind energy calculation purposes. The general representation of the Weibull distribution is given by:

$$f(\mathrm{V_{wind}}) = \left({}^{K}/_{C}\right)\left({}^{V_{wind}}/_{C}\right)^{k-1} \exp\left(-\left({}^{V_{wind}}/_{C}\right)^{k}\right) \qquad 2.1$$

Where V_{wind} is the wind speed (m/s), c is the scale factor of Weibull distribution with unit of speed, and k is the shape factor of Weibull distribution, which is dimensionless. There are several methods for calculating the parameters of the Weibull wind speed distribution for wind energy analysis [10]. In this paper we calculate the two parameters using:

$$K = \left({}^{\sigma_w}/_{V_{mean}}\right)^{-1.086} \quad \text{and } c = \frac{V_{mean}}{\Gamma(1+{}^{1}/_{K})} \qquad 2.2$$

Where the Γ( ) is the gamma function, V_{mean} is the average value of wind speed data, and σw is the standard deviation of wind speed data. The available wind generator power Pout can be expressed by a function of V_{wind}:

$$P_{out}(V_{wind}) = \begin{cases} P_{rated}.\frac{V_{wind}{}^{k}-V_{in}{}^{k}}{V_{in}{}^{k}-V_{rated}{}^{k}} & \text{if } V_{in} \le V_{wind} \le V_{rated} \\ P_{rated} & \text{if } V_{rated} \le V_{wind} \le V_{out} \\ 0 & \text{otherwise} \end{cases} \qquad (2.3)$$

Where P_{rated} is the rated power of the turbine, V_{in} is the cut-in wind speed, V_{rated} is the rated wind speed, V_{out} is the cut-out wind speed, k is the Weibull shape parameter. The distribution functions of the wind speed were calculated for every hour in a day. Then, the average output power of the wind turbine, whose specifications are provided by the manufacturer, can be calculated using the following equation:

$$P_{wind} = \int_{0}^{\infty} P_{out}(V_{wind}) \,.\, f(V_{wind}).\, d(V_{wind})$$

$$\int_{V_{in}}^{V_{rated}} (A + B\,.V_{wind}{}^{k})\,.\, f(V_{wind}).\, d(V_{wind}) + P_{rated}\,.\int_{V_{rated}}^{V_{out}} f(V_{wind}).\; d(V_{wind})$$

$$\text{Where, } A = {}^{P_{rated}V_{in}{}^{k}}\Big/_{(V_{rated}{}^{k} - V_{out}{}^{K})}, \text{ and } B = {}^{P_{rated}}\Big/_{(V_{rated}{}^{k} - V_{out}{}^{k})} \qquad (2.4)$$

2.2. Estimating the Output Power of PV Array

When there are different level of temperatures and irradiation effects on the PV module, the I-V characteristic of PV module could be different. The power generated by the PV array is not only dependent on the solar irradiation but also dependent on the ambient temperature of the site. A maximum power point tracker is often used in the PV array to reach the maximum output power at any radiation level [11, 12. The maximum output power at different radiation and temperature is calculated by the following equation:

$$P_S\,(G,\Delta T) = K_1.A_S.G.\,(1 - K_T\Delta T) \qquad (2.5)$$

Where A_S is the total area of the PV module (m^2), ΔT = Tc - T_{cref} is the temperature error of the PV module between the cell temperature Tc and the reference cell temperature Tcref (℃), kT is the temperature coefficient, and k1 is the PV module generation efficiency. Because of cloud cover and other insolation reducing phenomena, the solar irradiance G can also be represented by a random variable [13]. It has been shown that the beta distribution with parameters α and β can describe the solar irradiance

$$f_G(G) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{G}{G_{max}}\right)^{\alpha-1}\left(1-\frac{G}{G_{max}}\right)^{\beta-1} \qquad (2.6)$$

Where, the G_{max} is the maximum solar irradiance during a certain interval. The two parameters can be evaluated by the mean value μ_S and the variance σ_S as shown below:

$$\alpha = \mu_s\left[\frac{\mu_s(1-\mu_s)}{\sigma_s^2} - 1\right] \text{ and } \beta = (1-\mu_s)\left[\frac{\mu_s(1-\mu_s)}{\sigma_s^2} - 1\right] \qquad (2.7)$$

Once the solar irradiance and temperature were given for every hour of a day, the average output power of a PV array whose specifications are provided by the manufacturer can be calculated using Eq. (2.8):

$$P_S = \int_0^{G_{max}} P_S(G,\Delta T)\,.\,f_G(G)\,.\,d(G) \qquad (2.8)$$

3. Preliminary Sizing of System Elements

By considering each system elements independently, the preliminary sizes of the Genset, PV-arrays, Wind turbines, Battery bank and power converters are discussed in the next sections.

3.1. Preliminary Sizing of Genset

When there is no any support from the renewable energy and the battery bank, the Genset is sized based on the load demand in such a way that it should at least meet the peak load demand.

$$Pdg_{peak} = Pload_{peak} \quad \text{and} \quad P_{dg(t)} = P_{load(t)} \qquad (3.1)$$

During this condition, the Genset is controlled to follow the load demand and the following conditions are very importantly considered to model the "*Control of the Genset"* for simulation.

$$i, if\ 0 < P_{load(t)} < Pload_{peak}\ \ then\ P_{dg(t)} = P_{load(t)} \rightarrow$$

When the load connected at any time is within the peak power limit of the load profile which the Genset is normally sized for, and then the Genset is controlled to generate the load demand each time.

$$ii, if\ P_{load(t)} > Pload_{peak,}\ then\ P_{dg(t)} = Pdg_{peak} \rightarrow$$

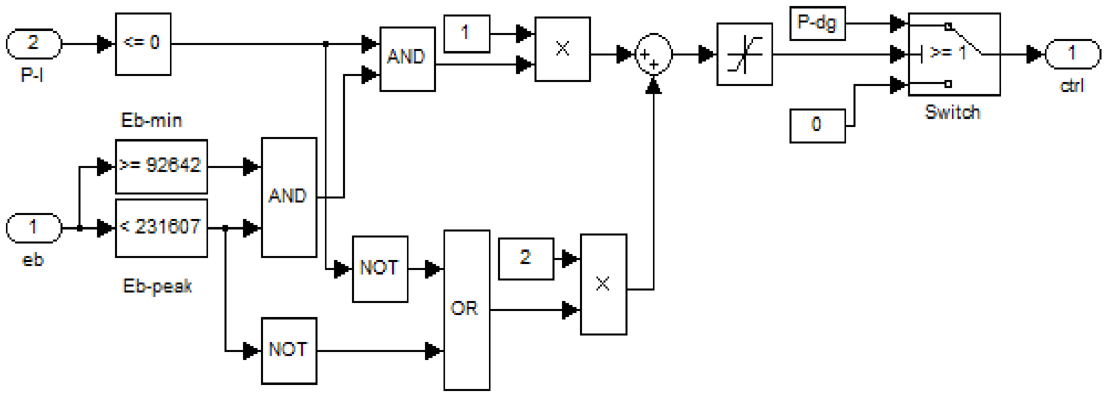


Figure 1: Detail of the "*Genset control*" sub-system

When a load greater than the peak power of the load profile which the Genset is sized for is suddenly connected, the Genset is only capably of supplying its peak power.

iii, if none of (i) and (ii) occurs, $P_{dg(t)}$ => when there is no load connected, the Genset should remain off.

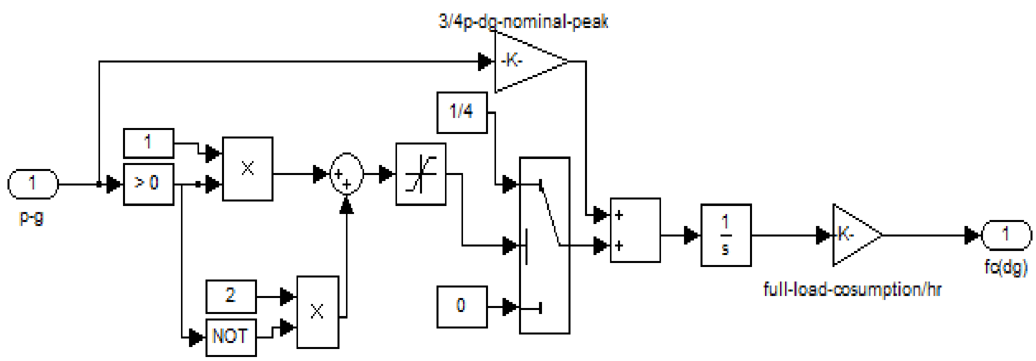


Figure 2: Detail of the „*Genset fuel consumption*" sub-system

3.2. Preliminary Sizing of the Battery bank

The battery bank is preliminarily sized in such a way that it is capable of storing enough energy from the renewable energy resources when there is plenty of supply. It, then, should supply the demand during low or no sun period and/or wind speed, alone or together with the RESs. The preliminary sizing of the battery capacity depends on the daily energy consumption (KWh/day).

$$\text{Battery capacity, BC} = \frac{E_{daily-load-demand} \times \mathbf{DOA}}{\eta_b\ \text{DOD}}\ (\text{Wh}) \qquad (3.2)$$

Where $E_{daily-load-demand}$ is the total daily energy demand (KWh/day), DOD is the depth of discharge of the battery, DOA is the days of autonomous (three day of autonomous is considered for this case) and ηb is the battery efficiency (85% in this case).

3.2.1. Battery Charging/discharging Control algorithm

When sizing the battery bank, much attention is paid to the minimum and maximum energy limits beyond which it shouldn't discharge and charge, respectively. "Charging and discharging control mechanism‟, is based on the energy limits of the battery (or SOC), the load demand and the supply. The following algorithm (**Figure 3**) depicts how the charging and discharging of the battery happens.

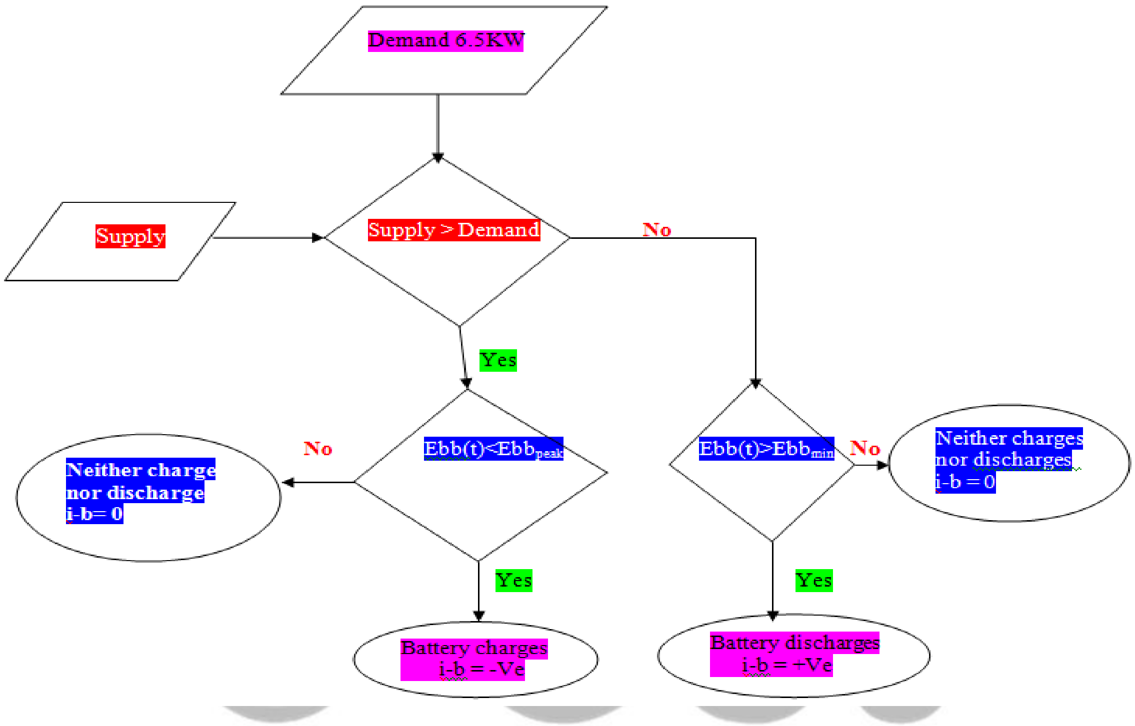


Figure 3: Battery Charging/Discharging control algorithm

The above algorithm shows the comparison of energies from the supply side and the demand side in the presence of rechargeable battery bank for testing its charging/discharging conditions. When the supply is greater than the demand, the battery bank enters into the charging state and the next condition is tested. With the first requirement at hand, the battery charges if the energy in the battery at any time is less than the maximum energy capacity of the battery. Otherwise, the battery will neither charge nor discharge though the supply still exceeds the demand. When the energy demand exceeds the supply, the battery may enter into the discharging mode to help supplying the load provided that the energy in the battery is greater than the minimum limit; otherwise it neither charges nor discharges.

3.2.2. Battery Charging/Discharging Controlling model circuit

Let's consider the following simple equivalent circuit model for a rechargeable battery bank connected with other elements at the DC-bus.

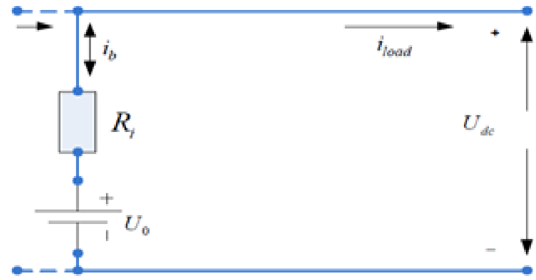


Figure 4: Simple equivalent circuit model of rechargeable lead acid battery

Applying a simple KVL, the voltage at the battery terminal can be expressed as:

$$U_{dc=}\ U_o - R_i i_o(\mathrm{t}) \qquad (3.3)$$

The power that is drawn from the battery is also given as:

$$P_{bb\,(t)} = U_{dc} i_{b\,(t)} \qquad (3.4)$$

The energy which is left in the battery after the load has drawn power from the battery can also be expressed as:

$$E_{bb}(\mathrm{t}) = E_{bb-init}(\mathrm{t}) - \int P_{bb}(\mathrm{t})\,\mathrm{dt} \qquad (3.5)$$

Where, U_{dc} = DC voltage at the DC-bus connection
U_o = Internal voltage of the battery bank
R_i = Internal resistance of the battery bank
i_b(t) = Current flowing out of the battery to the load (+Ve convention)
$E_{bb}(t)$ = Energy delivered to the load when the battery is discharging;
$E_{bb}(t) = E_{stor}(t)$ = (Stored energy) when the battery is charging
$E_{bb-init}(t)$ = Initial energy of the battery
P_{bb}(t) = power delivered to the load

The charging/discharging of the battery can be indicated by the presence of current flow. If the battery is neither charging nor discharging, there will be no current flow and thus no power is available in the battery. In this project, the charging or discharging modes are identified by the sign of battery current or power. According to the convention used in this project, a positive current or power shows the discharging mode and a negative current or power indicates the charging of the battery. When modeling for the simple electrical circuit that represents the rechargeable battery bank, three important points have to be considered. These are:

1. Battery state is neither minimum nor full

When the battery is neither at its lowest state nor at its full state ($E_{bb-min} < E_{bb}(t) < E_{bb-peak}$), it can either charge or discharge depending on the load demand and other energy source conditions. Whenever there is more supply from other sources than the demand, it charges and when the demand exceeds the supply, it discharges.

2. Battery has been fully charged and load draws power from it

This is the case when the battery is fully charged and it is discharging when the load draws power from it. Depending on the energy sources and the load demand, the conditions which have to meet:

$$E_{bb}(t) = E_{bb-peak} \ and \ P_{load}(t) - P_{generated}(\mathrm{t}) > 0 \qquad (3.6)$$

3. Battery has been discharged to its minimum energy and it is charging

When the battery has been discharged to its minimum state, and there is more supply than there is demand, the battery charges. The condition which must be fulfilled during this situation is:

$$E_{bb}(t) = E_{bb-min} \ and \ P_{load}(t) - P_{generated}(\mathrm{t}) < 0 \qquad (3.7)$$

If none of the above three conditions happens at any time, the energy of the battery, hence, remains constant; and as a result i_b (t) and $P_{bb}(t)$ will be zero. Based on the above set of equations, the battery bank subsystem can be modeled in the following manner.

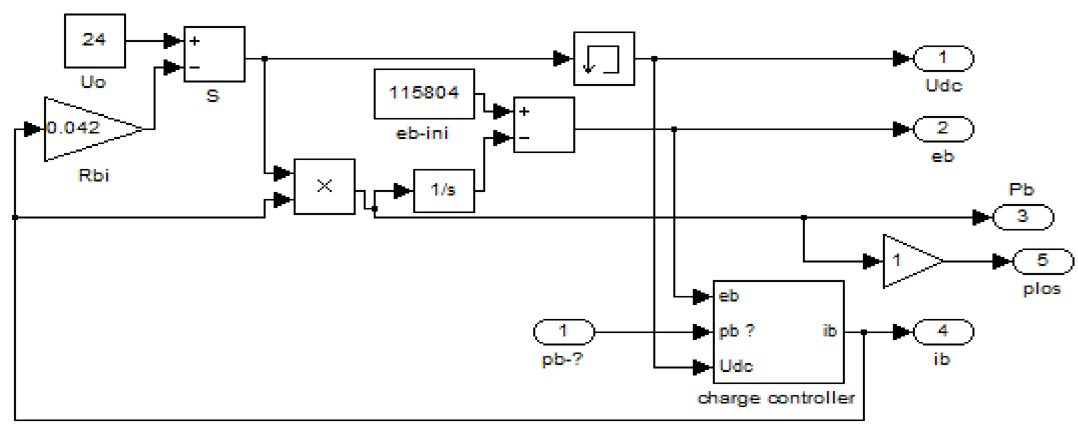


Figure 5: MATLAB Simulink model of the rechargeable lead acid battery

Based on the above discussion *"Charging/Discharging Control mechanism"* of the battery bank is shown in Figure 6 below.

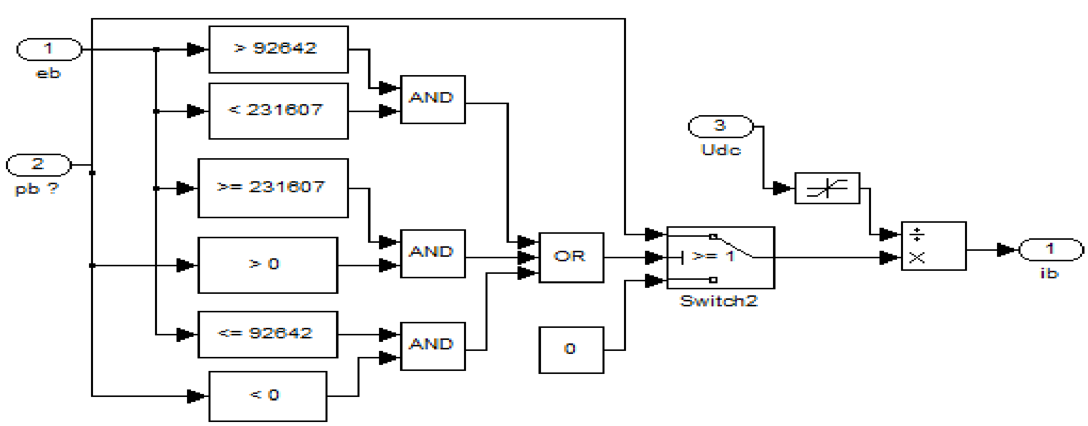


Figure 6: Detail of the „*Charging/Discharging Control*" of the battery bank

3.3. MATLAB/Simulink Modeling for PV/Wind/Generator/Battery

The Simulink model accepts three basic inputs. These include data inputs from the load demand, the solar power (from solar irradiation) and the wind turbine power (from speed). The details of the „*Battery bank*" sub-system and its „*Charging/discharging control*" are given.

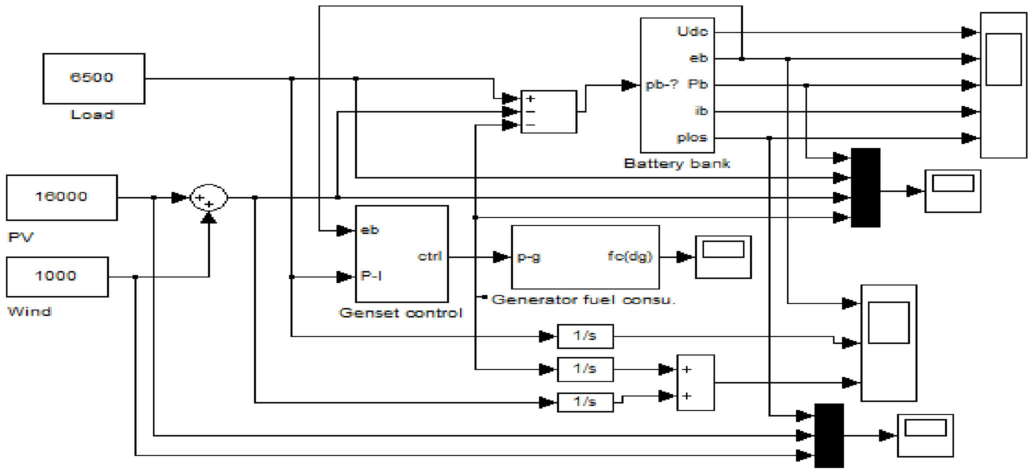


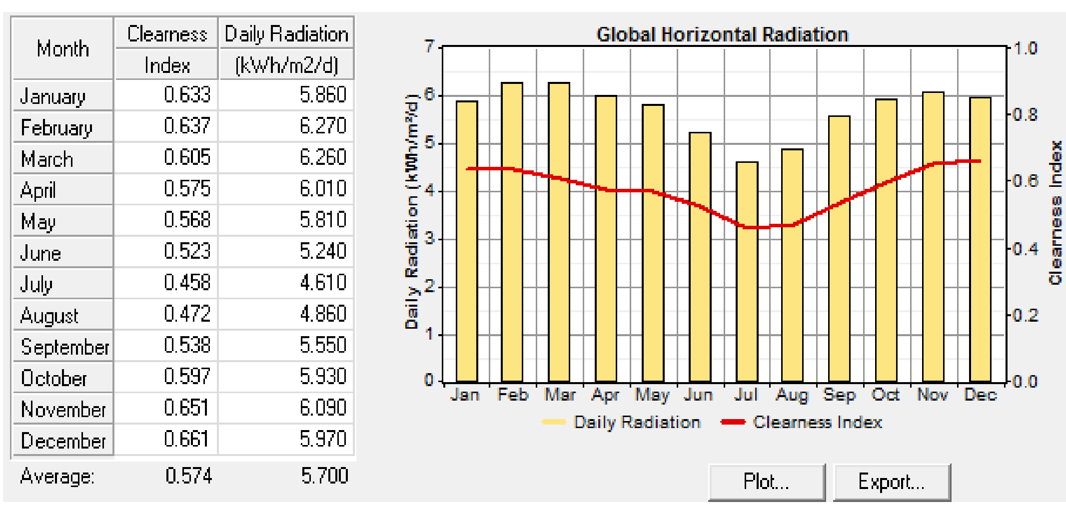
Figure 7: MATLAB/Simulink model of Renewable source, Battery and Generators

4. Feasibility of the hybrid system

This project work, the feasibility study into the establishment of PV/wind/Genset electric energy supply system to a Faji High School for all appliances will be carried out.

4.1. Renewable Energy Resource

The renewable energy potentials (solar and wind) and temperature data of the study area are presented below. Temperature data's is to consider temperature effect in the system. NASA data's and previously studied data's are compared and the best is taken.



Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.633	5.860
February	0.637	6.270
March	0.605	6.260
April	0.575	6.010
May	0.568	5.810
June	0.523	5.240
July	0.458	4.610
August	0.472	4.860
September	0.538	5.550
October	0.597	5.930
November	0.651	6.090
December	0.661	5.970
Average:	0.574	5.700

Figure 8: Solar radiation Potential of site

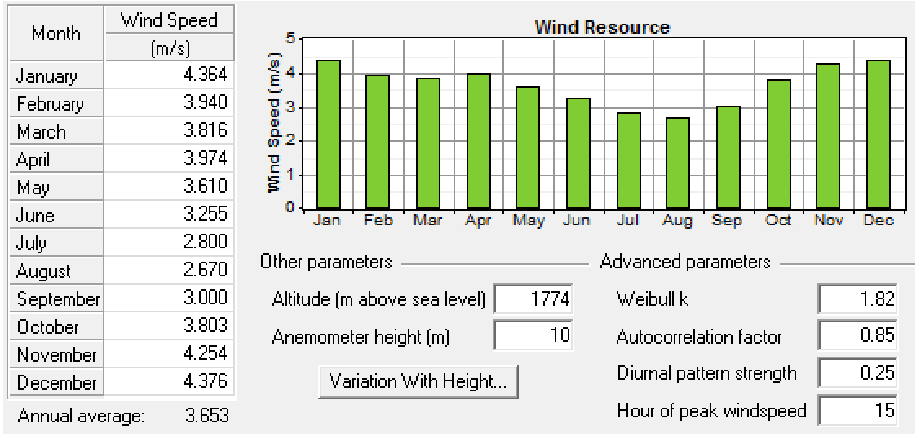


Figure 9: Wind speed potential of site

4.2. System Load Profile

The load of school is 6.645KW or 65.622KWh which is analyzed hourly load data, HOMER formed load curves in daily and monthly profiles. The most descriptive graph shown in figure-4 depicts the variation in demand on hourly basis.Figure-4.3 shows that the school appliances have a load in an operating time.

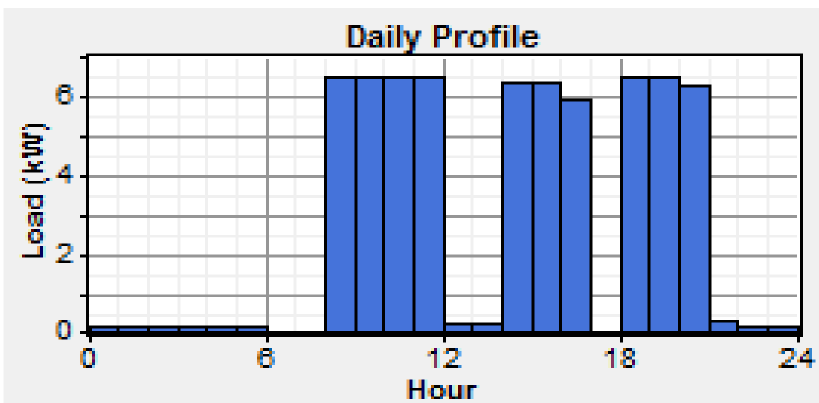


Figure 10: Daily load profile on the hourly basis

4.3. Homer Model of the System

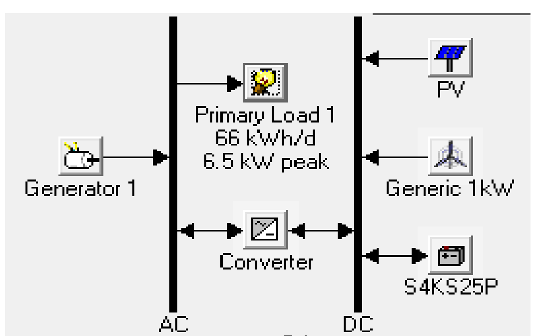


Figure 11: HOMER model of the system

Table-1 Summary of inputs for system optimization

	PV	Wind	Generator	Battery	Converter
Unit	KW	KW	KW	Ah	KW
Size	11	1	4	1708	8.5
Capital cost ($)	16500	1200	1600	1573	5950
Replacement cost ($)	16500	960	1280	1230	5950
O & M cost ($/yr)	0	24	683	30	0
Size to consider	12,14,16,18	………..	3,4,5,6,7	……….	6,7,8,9,10
Quantities Considered	…………..	1,2,3,4	………….		………
Life time (yr)	25	25	8	12	15

4.4. Optimization Result

From the following overall optimization result one can see that the feasible optimum PV/Wind/ Genset/ Battery combination system types are formed. In any case, the best Hybrid Feasible Optimum System for this study is in the 16th rank with a total NPC of $78,251 having a COE of $0.274/kWh.

Table 2. System arctechture for 78% renewable and 22% nonrenewable penetrations

PV array	16KW
Wind Turbine	1KW
Generator	4KW
Battery	4×1708Ah
Converter	8KW

Table .3 Annual electric productions in (KWh/yr)

PV array	26,946	77%
Wind turbine	368	1%
Generator	7,566	22%
Excess electricity	9735	27.9
Unmet electric load	1625	6.8
Capacity shortage	2324	9.7
Renewable fraction	0.783	78.3%

Annual Electric Consumption (kWh/yr.)		
AC Primary Load	22,320	100%
Total	22,320	100%

Cost summery	
Total NPC	$78,251
Levelized COE	$0.274/kwh
Operating Cost	$3,106/yr

Table 4. *Feasible overall optimization result table*

PV (kW)	G1	Label (kW)	S4KS25P	Conv. (kW)	Efficiency Measures	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	opy of Diese (L)	Label (hrs)
16		4	4	8	No	$ 37,348	3,118	$ 77,211	0.271	0.78	0.10	2,657	2,308
16		4	4	8	Yes	$ 37,348	3,118	$ 77,211	0.271	0.78	0.10	2,657	2,308
17		4	4	8	No	$ 38,848	3,012	$ 77,347	0.271	0.79	0.10	2,556	2,210
17		4	4	8	Yes	$ 38,848	3,012	$ 77,347	0.271	0.79	0.10	2,556	2,210
15		4	4	8	No	$ 35,848	3,251	$ 77,402	0.273	0.76	0.10	2,783	2,429
15		4	4	8	Yes	$ 35,848	3,251	$ 77,402	0.273	0.76	0.10	2,783	2,429
14		4	4	8	No	$ 34,348	3,397	$ 77,773	0.275	0.74	0.11	2,925	2,558
14		4	4	8	Yes	$ 34,348	3,397	$ 77,773	0.275	0.74	0.11	2,925	2,558
18		4	4	8	No	$ 40,348	2,929	$ 77,791	0.272	0.81	0.09	2,476	2,137
18		4	4	8	Yes	$ 40,348	2,929	$ 77,791	0.272	0.81	0.09	2,476	2,137
13		4	4	8	No	$ 32,848	3,542	$ 78,126	0.278	0.71	0.11	3,069	2,681
13		4	4	8	Yes	$ 32,848	3,542	$ 78,126	0.278	0.71	0.11	3,069	2,681
16		4	4	9	No	$ 38,048	3,137	$ 78,149	0.275	0.78	0.10	2,657	2,308
16		4	4	9	Yes	$ 38,048	3,137	$ 78,149	0.275	0.78	0.10	2,657	2,308
16	1	4	4	8	No	$ 38,548	3,106	$ 78,251	0.274	0.78	0.10	2,621	2,278
16	1	4	4	8	Yes	$ 38,548	3,106	$ 78,251	0.274	0.78	0.10	2,621	2,278
17		4	4	9	No	$ 39,548	3,030	$ 78,284	0.274	0.79	0.10	2,556	2,210
17		4	4	9	Yes	$ 39,548	3,030	$ 78,284	0.274	0.79	0.10	2,556	2,210
15	1	4	4	8	No	$ 37,048	3,230	$ 78,335	0.275	0.76	0.10	2,739	2,390
15	1	4	4	8	Yes	$ 37,048	3,230	$ 78,335	0.275	0.76	0.10	2,739	2,390

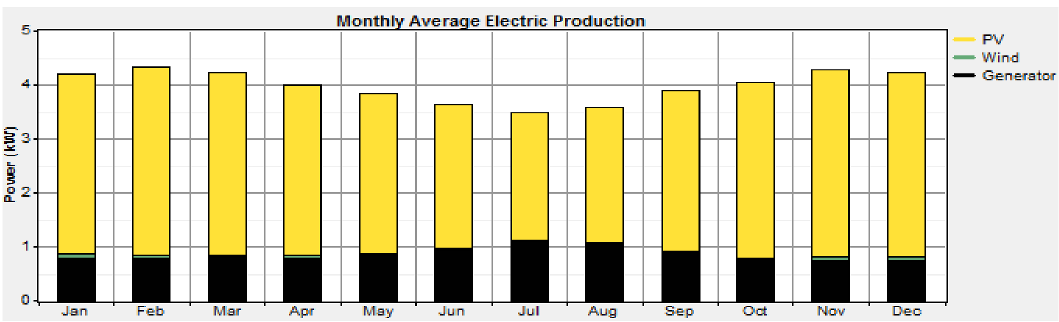


Figure 12: *Monthly average electric production for the optimum PV/Wind hybrid system*

5. CONCLUSION

In this paper, the optimization, dynamic modeling and control of AC hybrid source for School application have been presented. This system is composed of a wind turbine, PV, Geneset and a battery. It has been verified that photovoltaic module, a wind turbine and Geneset is used to charge the battery minimum load and peak load discharge of the battery is used to directly feed the appliances. The battery charging and discharging control algorithm and its equivalent circuit was developed as a component of system dynamic model. Simulation of the whole system is also given. The 24 hour dynamic response gives good functioning and a correctly attempt objectives.

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