Energy Management Strategy for Grid-Networks of Distributed Generation

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Abstract- Energy management and control are major factors of importance in this revolutionary era of power system. The revolution in renewable energy generation and its utilization mandate to develop and adopt energy management strategies. Considering the dynamic behavior of renewable energy sources and load, a systematic control and energy management strategy is developed. The aim of this paper is to implement real time supervision and energy management of a hybrid system for efficient utilization of renewable energy resources. With this aim of real time supervision and energy management, a controlled and energy management strategy is developed. This developed energy management strategy can be imposed on any size of off-grid and grid connected distributed generation system. A grid connected distributed generation system is considered. This distributed generation system is a hybrid renewable energy system. The hybrid renewable energy system is a combination of two or more renewable energy sources such as solar energy, wind energy and biomass energy to increase reliability and efficiency of a system and battery is used as a storage to provide balance in energy supply. MATLAB is used to develop energy management strategy and different cases are analysed. The effectiveness of energy management strategy on hybrid system is explored and its results are presented.

Keywords- Energy management 1, Grid network 2, Distributed generation 3, Hybrid system 4.

Acronyms-

I_{lg} – Light generated current
I_{sc} – Short circuit current
I_D – Cell reverse saturation current
I_{PV} – Solar cell output current
I_p – Solar panel output current
I_T – Total solar radiation in W/m^2
A_T – Total area of a PV module/panel in m^2
η – Overall efficiency of the PV system
V_{PV}- Solar cell output voltage
V_P- Solar panel output circuit voltage
q – Electron charge (1.6×10^{-19}C).
R_s –Series resistance
K_B – Boltzmann constant (1.38×10^{-23} J/K).
T – Temperature.
A – Area of panel/module
N_s – Number of PV cell connected in series
N_p – Number of PV cell connected in parallel
P_p – Electrical power output of wind turbine
P_{PT} – Total power output of a PV system
$f_w(v)$ – Weibull probability density function for wind velocity.
$f_w(v,k,c)$ – Weibull distribution function for variables v, k, c.
k – Dimensionless shape parameter
c – Dimensions scale parameter
v – Wind velocity
P_o – Electrical power output of wind turbine
$P_{o\ avg}$ – Average power of a wind
P_{BGS} – Hourly electrical power output for biomass gasification system in kW
P_{BDS} – Hourly electrical power output of biomass digester system in kW
ES – Energy storage.
SoC – State of charge of a battery.
$\eta_{c(t)}$ – Charge efficiency factor depending on charging current
$I_{b(t)}$ – Charging current at time (t)
C_b – Nominal capacity of the battery in A

1. Introduction

A conventional power generation system has provided reliable power since the last one hundred years, but due to fear of depletion in conventional energy sources, increasing energy demand of next generation and threat of increasing pollution and population, there is a need to have fast revolutionary changes in the power sector. This necessitates to develop and adopt renewable energy sources, which at present act as a support to a conventional sources and conventional power sector but in near future they could dominate the conventional energy sources. To support depleting convensional energy sources, large development and installation are made in macro renewable power generation system, which is directly fed to the grid. This macro renewable power generation system may reduce the consumption of conventional energy sources but cannot reduce the transmission, distribution, switching and contact losses, whereas distribution losses are reduced in Ref. [17]. A practical experience at Babupet, Chandrapur, Maharashtra, India, where the distribution company was facing 45-47 percent loss in transmission, distribution and in contacts, while providing power to this large distribution area. In order to reduce the losses the company has divided this large area of distribution network into smaller distribution pockets and looping these small distribution pockets with short distance transmission lines. Each distribution pocket contains 40-50 small consumers and a 25kVA transformer. This concept of creating a small distribution pockets brings the losses to 7-8 percent, minimizes the outage of total area and increases the power supply reliability. This concept of small distribution pockets, motivates for developing small energy generating units of sizes like Micro, Nano, Pico and Decentralized generation as a distributed generation system. This distributed generation pattern have many more advantages such as reduction in transmission, distribution, switching and contact losses. It does not only reduces the burden on conventional sources but also decreases the environmental pollution. This distributed generation also improves the power supply quality, reliability, choice flexibility and instills confidence of self development [18-19].

In this paper grid connected distribution generation is considered for both urban and rural area. The cited grid conected hybrid system consists of three renewable energy sources according to the availability, such as solar, wind and biomass to fulfill the load requirement. The lead acid battery as an energy storage device is used to manage small load fluctuations and energy balance. Solar and wind plant capacities are considered in a way to fulfill maximum load demand as a base load. Where as biomass and biogas plants are for peak load fulfillment and also as a backup during low generation from solar and wind.

The energy management unit is used to manage energy flow among the various generating units. In an energy management flow in Fig.1, all the energy generating and consuming units are connected to an energy management unit, in which all controlling and switching operation are carriedout. The energy management and control among different renewable energy sources and load are done by using MATLAB.

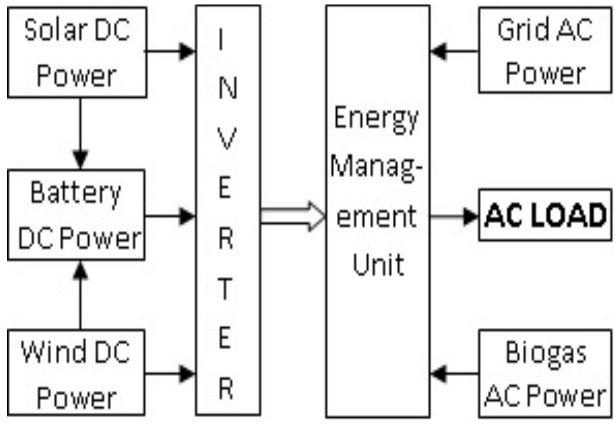

Fig 1. Energy Management flow.

This paper mainly focuses on developing efficient energy management strategy with the aim to utilize and save the generated renewable energy and to satisfy maximum load demand. This paper does not consider economical aspects as it does not make more cost saving for small distributed generation, but proper planning of unit size and load consideration is important. Load co1nsideration or load scheduling and unit sizing are another broad aspects, which can be carried out mathematically or by using optimization techniques.

2. Grids Structure Consideration

Numerous studies have been conducted on distributed generation by considering various grid levels such as micro-grid, nano-grid, pico-grid and decentralized system for various research projects. There are many perspectives on micro-grid and nano-grid paradigms along with some new perspectives on pico-grid and decentralized paradigm of power system discussed in the literature. Ref. [1] which explains different networks such as micro-grid, nano-grid, and pico-grid system, Ref. [2] explains nanogrid system and Ref. [20] proposes decentralized energy generation system". Table 1 shows different grid networks used for distributed generation system [21].

According to Ref. [19] and other literature surveys the micro-grid is of 1 MW to 20 MW generation (micro-hydro, micro-wind, biomass boiler) and encompasses a group of houses up to the grid distribution network. In Ref. [1] micro-grid is defined as "It is a low voltage distribution network comprising various distributed generation, energy storage devices and considerable load that may be grid connected or off-grid (isolated from power distribution grid)".

According to Ref. [2] and other literature surveys the nano-grid is of 10 kW to 100 kW generation (solar PV, small wind turbine, biogas, diesel generator) and encompasses few average load houses and 6-8 apartments of a building. In Ref. [2], nano-grid is defined as "It is a low voltage distribution network comprising various distributed generation, energy storage devices and considerable load that may be grid connected or off-grid (isolated from power distribution grid)".

Table 1. Distributed Generation Grids.

Grid Type	Grid Limit	Load Limit	Type of Load	Ref.
Micro Grid	1-20 MW	1-20 MW	50-300 houses	[2]
Nano Grid	10-100 kW	10-100 kW	6-8 flats	[3]
Pico Grid	01-10kW	01-10 kW	Single house	[2]
Decentral-ized Grid	0-1 kW	0-1 kW	DC loads of a single house/s	[4]

According to Ref. [1], pico-grid is of 1 kW to 10 kW generation (solar PV, small wind turbine, biogas, battery) and encompasses single house with load-shifting, peak-saving and other energy saving devices. In Ref. [1], pico-grid is defines as "An aggregation of the manageable loads connected in single small house to carry out load-shifting, peak-shaving and energy management algorithm".

In Ref. [20], decentralized system consisting DC grid was explained. Decentralized paradigm of DC grid consisting of decentralized generation (solar PV, DC wind turbine, battery, and ultra capacitors) and electronic devices in household/building operates on DC current (computer, multimedia, air conditioners).

3. Mathematical Modeling of Renewable Energy Sources

This section consists of mathematical model of aforementioned renewable energy sources such as solar PV, wind, biomass, biogas and battery for optimal unit sizing [3].

3.1 Mathematical Model for Solar PV system

The solar PV system is used to convert solar energy into electrical energy. As the solar radiation falls on PV cells, it produces voltage and current at its terminals. The generation of electrical energy depends on solar radiation incident on PV cell.

Based on the basic circuit of PV cell as in Fig. 2, the output current of PV panel I_p with series parallel combination of PV cells is given in the Eq. (1). The open circuit voltage of the PV panel V_p with series parallel combination of PV cells is given in the Eq. (2). The number of PV cell connected in series is N_s and number of PV cell connected in parallel is N_p [4, 19].

$$I_p = N_p . I_{lg} - N_p . I_o \left[\exp\left(\frac{q(V_{pv}+I_{pv}.R_s)}{K_B.T.A.N_s}\right) - 1\right] \text{Amp} \quad (1)$$

$$V_p = N_s . V_{pv} \quad \text{Volts} \quad (2)$$

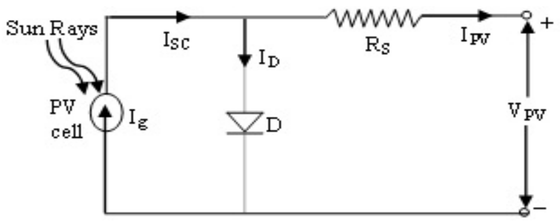

Fig 2. Basic circuit model of PV solar cell.

The maximum power output P_p of PV panel can be calculated once solar radiation on the PV module and ambient temperature were found [5].

$$P_p = V_p . I_p \quad \text{Watts} \quad (3)$$

The power output of PV system is when a total solar radiation of I_T (W/m^2) is incident on the surface area of PV module and is given by the Eq. (4) [22].

$$P_{PT} = I_T A_T \eta \quad \text{Watts} \quad (4)$$

where, P_{PT} is the total power output of a PV system in W, I_T is the total solar radiation at time t (W/m^2), A_T is the total area of a PV module (m^2), η is the overall efficiency of the PV system.

3.2 Mathematical Model for Wind system

The wind speed is dynamic and changes continuously. Wind changes with change in weather, temperature, height and many other factors. Wind always flows in a particular pattern, to harness wind energy it is needed to study the wind pattern. For maximum and efficient generation of wind power and to access the energy potential it is necessary to critically analyze on the wind data which is highly site dependent [6]. For predicting energy output of wind energy conversion system, it important to have a proper knowledge of statistical properties of wind speed. For obtaining the statistical distribution of wind speed data, following methods were used to calculate the wind power density frequency distribution function like Weibull distribution, Rayliegh distribution, Gama distribution, log normal distribution etc. Out of these distribution functions, the two parametric Weiball Probability Density Function [PDF] is usually considered as a most appropriate function due to its high accuracy and simplicity. The two parameters of Weibull PDF is recommended by international standard IES 61400-12 and other international, as it is the most appropriate distribution function for wind speed data which gives a good fit to the observed wind speed data both at surface and in the upper air and also for estimating wind energy potential at various locations worldwide[7-9]. Thus, from the conclusion of Ref. [11] it is considered that for low wind speed range, Weibull model is an adequate model to the wind climate of the stations in India. These two parameters of Weibull distribution are characterized by dimensionless shape parameter 'k' and dimensions scale parameter 'c' in m/s [10]. The Weibull probability density function is considered as best for low and variable wind speed [11]. The Weibull probability density function for wind velocity (v) is given by the Eq. (5).

$$f_w(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{(k-1)} \exp\left[-\left(\frac{v}{c}\right)^{(k)}\right] \quad (5)$$

The average power of wind is the product of power produced at a particular wind speed to the function of time that the wind speed is experienced and integrating overall possible wind speed. The average power in integral form is given by the Eq. (6).

$$P_{oavg} = \int_0^{\infty} P_o \cdot f_w(v,k,c) \cdot dv \;\; \text{Watts} \quad (6)$$

where, P_o is electrical power output of wind turbine, $f_w(v,k,c)$ is Weibull distribution function.

If Weibull probability distribution function is considered as best for low and variable wind speed, the average power of a wind is given by the Eq. (7).

$$P_{oavg} = \int_0^\infty P_o \cdot f_w(v) \cdot dv \text{ Watts} \quad (7)$$

where, $f_w(v)$ is the Weibull probability density function.

3.3 Mathematical Model for Biomass Gasification based System

The less moisture content biomass is used to generate gas by the process known as gasification. Gasification is the matured thermo-chemical method of biogas generation in an isolated area for electrification. The gas generated by gasification is used either in dual-fuel engines or diesel engines. This engine is started with diesel and runs on gas and diesel mixture in the ratio of 2:3 [12]. The electric generator is coupled to the diesel engine, which act as a prime mover to an electrical generator is known as DG set (Diesel-Generator set) to produce electrical power. The electrical power output also depends on different biomass material of different calorific value (CV_{BM}), overall conversion efficiency of the system (η_{system}) and working hour per day of system ($H_{/day}$). The biomass consumption rate varies from 1.2 -1.5 kg for wood and 1.8 – 3.6 kg for rice husk to produce 1kWh of energy for appropriate gasifier system with internal combustion engine. If internal combustion engine is run on duel fuel, 0.9 – 1.1kg of biomass and 0.09 – 0.11liter of diesel is used and if it runs on only producer gas 1.2- 1.6 kg of biomass is required to generate 1kWh energy [15]. Mathematical model of generated electrical power by biomass gasification process is given by the Eq. (8) [23].

$$P_{BGS} = \frac{\text{Biomass Material(Kg/day)} \times CV_{BM} \times \eta_{system} \times 1000}{860 \times H/day} \text{ Watts} \quad (8)$$

where, P_{BGS}– Hourly electrical power output for biomass gasification system in kW.

From numerous studies of gasification, 1 kg/hr. input of biomass material can convert into gas of volume which can generate 1 kW of electricity [24].

3.4 Mathematical Model for Biomass Digestion based (Biogas) System

The large moisture content biomass is used to generate biogas by the process known as digestion. Digestion is another matured and bio-chemical conversion method of biogas generation in an isolated area for electrification and cooking. The gas generated with this digester system is used either in dual-fuel engines or in a diesel engine with diesel. This engine is started with diesel and runs on gas and diesel mixture in the ratio of 2:3 [12]. The electric generator is coupled to the diesel engine, which act as a prime mover to an electrical generator is known as DG set (Diesel-Generator set) to produce electrical power. The electrical power output also depends on biomass material as different biomass material is of different calorific value (CV_{BM}), overall conversion efficiency of the system (η_{system}) and working hour per day of system ($H_{/day}$). 1m^3 of biogas can be converted only to around 1.7 - 2.0kWh electrical energy. Mathematical model of generated electrical power by biomass digestion process is given by the Eq. (9) [23].

$$P_{BDS} = \frac{\text{Biogas Generated}(m^3/\text{day}) \times CV_{BG} \times \eta_{system} \times 1000}{860 \times H/day} \text{ Watts} \quad (9)$$

where, P_{BDS}– Hourly electrical power output of biomass digester system in kW.

The gases produced in anaerobic digestion are ethanol and methane, which are considered as a clean and ideal fuel. The energy produced by 1 kg of methane gas is 15.4 kWh which is twice that of ethanol gas [25].

3.5 Mathematical Model for Energy Storage System

For hybrid renewable energy generating system, application of energy storage (ES) system is necessary. It is necessary to have a proper selection of the size of ES system. For proper sizing of ES system, it needs a complete analysis of renewable sources power output pattern, load pattern, operating temperature, efficiency of charger and other systems components, battery charging and discharging etc. Lead acid battery is one of the popular ES systems for quality and reliability. The response of a lead acid battery is 20 msec. to compensate between the sources and load transients. Related to hybrid renewable systems performance the state of charge (*SoC*) of a battery during charging and discharging is given by the Eq. (10) & Eq. (11) [13].

1. *The SoC of a battery during charging is–*

$$SoC_{t+1} = SoC_t[1 - \sigma(t)] + \left[\frac{I_{b(t)} \times \Delta t \times \eta_{c(t)}}{C_b}\right] \quad (10)$$

where, $\eta_{c(t)}$ – charge efficiency factor depending on charging current and *SoC* of a battery and has a value between 0.65 - 0.85, $I_{b(t)}$ – charging current at time (t) for the hybrid PV-Wind power conversion system.

2. *SoC of a battery during discharging is–*

$$SoC_{t+1} = SoC_t[1 - \sigma(t)] - \left[\frac{I_{b(t)} \times \Delta t \times \eta_{c(t)}}{C_b}\right] \quad (11)$$

where, $\eta_{d(t)}$ – discharging efficiency factor is generally taken as 1, I_b – charging current at a time (t).

4. Energy Management Algorithm

The energy management strategy was developed after investigating the performance of aforementioned renewable sources for proposed hybrid system using MATLAB. For the proposed hybrid system, different renewable sources need adequate control and management strategy for efficient utilization of generated power [14, 26]. Fig. 2 shows flowchart for control and energy management algorithm for the proffered hybrid system. Battery charging is incorporated in the algorithm but not shown in flowchart. The control and energy management strategy of proffered hybrid system is applicable to micro, nano and pico distributed renewable energy generating system. For decentralized distributed generation only DC power generating renewable sources are preferred such as solar PV, DC wind turbine and fuel cells.

The algorithm of energy management is explained below and flowchart is shown in Fig. 2. In this system, the cumulative capacity of renewable energy sources like solar PV, wind turbine and battery are so considered that they can manage and fulfill maximum load demand as a base load. Renewable energy sources conidertion and their preference of selection are decided depending upon the availability of sources at a specific location. The location like Chandrapur, M.S., India, which has very high solar insolation, hence the first preference is given to solar and then to wind and battery. At first the connectivity of all inputs of aforementioned renewable energy sources and load are checked. The generated power from solar and wind sources are first preferred to satisfy load and surplus power after satisfying load is used to charge the battery. As per the developed energy managment steategy the algorithm and energy flow steps are explained below –

The load is first compared with generated solar power, if solar power is greater than load demand, then solar system is connected to feed the load and if there is an excess solar power after satisfying load it is fed to the battery for charging.

Load ≤ Generated Solar Power (Connect solar system to feed the load).

If generating solar power is less than the load demand, then this insufficient solar power is used to charge the battery, next wind power is checked and if wind power is greater than load demand, then connect wind system to feed the load and if there is an excess wind power after satisfying load it is fed to the battery for charging.

Load ≤ Generated Wind Power (Connect wind system to feed the load).

If generated solar power and wind power individualy is less than the load demand, then cumulative of both solar power and wind power is considered. The cumulative of both solar and wind power is checked and if it is greater than load demand, then connect solar and wind system to feed load and if there is an excess power from both the sources after satisfying load it is fed to the battery for charging.

Load ≤ Generated Solar Power + Generated Wind Power (Connect solar and wind to feed the load).

If generated solar power and wind power is less than the load demand, then battery is added to both solar power and wind power. The cumulative of solar, wind and battery power is checked and if it is greater than load demand, then connect solar, wind and battery system to feed load. Before connecting battery it is checked that battery charging is not less than 20%, so as to avoid deep discharging. If battery charge reaches to 20% during serving it will stop serving the load.

Load ≤ Generated Solar Power + Generated Wind Power + Stored Battery Power (Connect solar, wind and battery system to feed the load).

If cumulative of solar power, wind power and battery power is less than the load demand, and then the biogas power is checked. Biogas plant is used to run same dual-fuel engine as a generator. If stored biogas from biomass is ≤ 50%, then dual-fuel engine is used to provide power to the load. This dual-fuel engine is preferred to run when cumulative of solar, wind and battery power is insufficient and also during peak load period. The generated power from solar and wind is then used to charge the battery when dual-fuel engine is providing power to the load.

Load ≤ Generated Biogas (if biogas ≥ 50%) (Connect dual-fuel engine to feed the load.

As it is a grid connected distribution system, if any of these renewable energy sources are unable to generate power due to various reasons like natural calamities, unfavorable environmental conditions and during maintenance then lastly the load demand is fulfilled by grid power i.e. grid will serve power to the load. The care should be taken that load will continuously getting power and bringing in and out of the sources during charging.

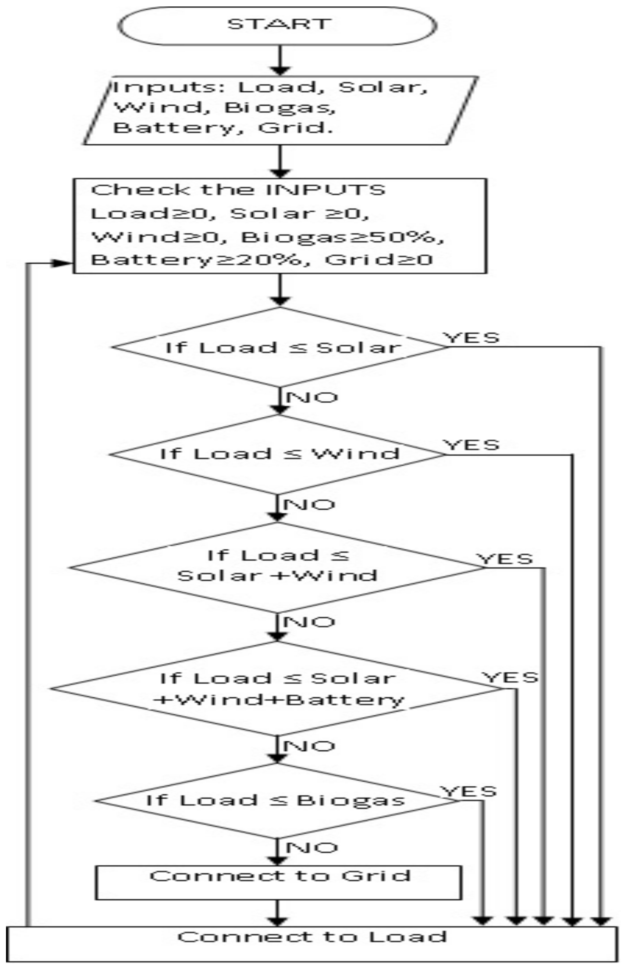

Fig 3. Energy Management flowchart.

5. Result and Discussion

Considering some random cases at different operating conditions of a developed energy management strategy and successful results of MATLAB program are discussed. An aforementioned energy management strategy on grid connected hybrid (solar-wind-biomass-battery) system, which satisfies the load at different conditions by connecting and serving the load from available sources is also discussed. By considering some cases and to get the results of developed energy management strategy, the input parameters and their capacity limits are considered. Summary of considered input parameters and considered maximum capacity limit is given in the Table 2. According to energy management flow diagram as in Fig.1, battery charging current is not incorporated in Fig. 3 of energy management flowchart as and in Fig. 4-8 of energy management results. The summary of energy management results of Fig. 4-8 is represented in the Table 3.

As it is stated above, solar power is given the first preference, second preference to wind power, third to battery, fourth to biogas and then to grid as in Fig. 3. Let us consider Fig. 4 that shows solar power is connected to a load. As the solar power generation is greater than connected load demand, the solar power is serving the load. The surplus power from solar at this instant and the wind power of 1500W is used to charge the battery. Biogas developed from biomass is stored for future use. Grid power is not connected.

As shown in Fig. 5 both solar and wind powers are connected to the load. As solar power alone does not satisfy the load demand, then wind power is added with solar power. If they both can satisfy the load demand, then solar and wind both are used to serve the load. The surplus power from solar and wind is used to charge the battery. Biogas developed from biomass is stored for future use. Grid power is not connected.

As depicted in Fig. 6 solar, wind and battery powers are connected to the load. As both solar and wind powers are unable to satisfy the load demand then battery is added with solar and wind power. If the combination of three satisfy the load demand, then these three sources (solar, wind and battery) are serving the load. As battery is also serving the load, hence battery is discharged here. Biogas developed from biomass is stored for future use. Grid power is not connected.

Table 2. Input parameters and its max. generated capacity

Sr. No.	Sources Considered	Max. Capacity
1	Solar	1000 W
2	Wind	2000W
3	Battery	4000W
4	Biogas	5000W
5	Grid	10000W
6	Load	10000W

Table 3. Summary of results in Fig. 4-8 for energy flow of developed energy management strategy.

Fig. No.	Sources Connected	Power output of connected source	Source Voltage	Generated Current	Load Connected	Load Voltage	Current delivered to load by each source	Battery Charging Current
4	Solar	700W	230V	3.0434A	600W	230V	2.6087A	2.6087A
5	Solar	500W	230V	2.1739A	1200W	230V	2.1739A	0.8695A
	Wind	900W		3.9130A			3.0435A	
6	Solar	1000W	230V	4.3478A	3000W	230V	4.3478A	0.8696A
	Wind	500W		2.1739A			2.1739A	
	Battery	1700W		7.3913A			6.5217A	
7	Biogas	4850W	230V	21.0869A	4220W	230V	18.3478A	-------
8	Grid	10000W	230V	43.478A	3665W	230V	15.9348A	-------

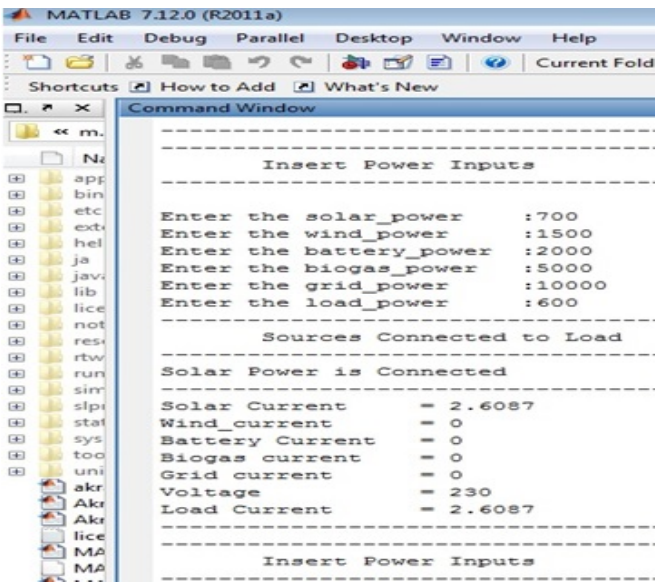

Fig 4. Solar power serving load.

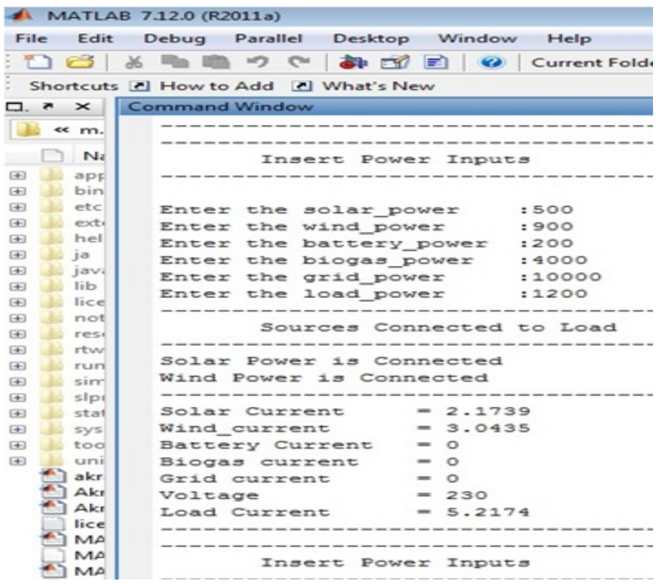

Fig 5. Solar and wind power serving load.

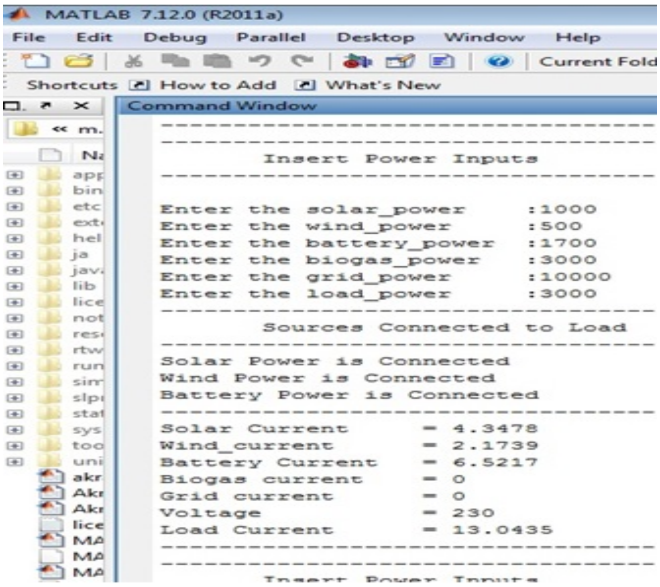

Fig 6. Solar, wind and battery power serving load.

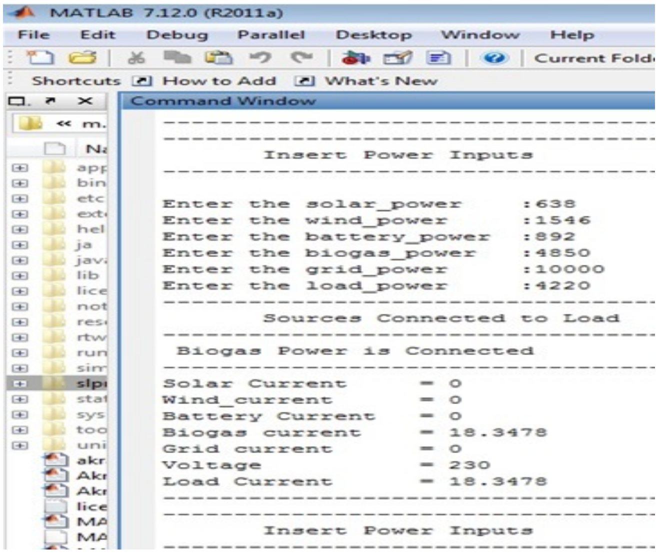

Fig 7. Biogas plant serving load.

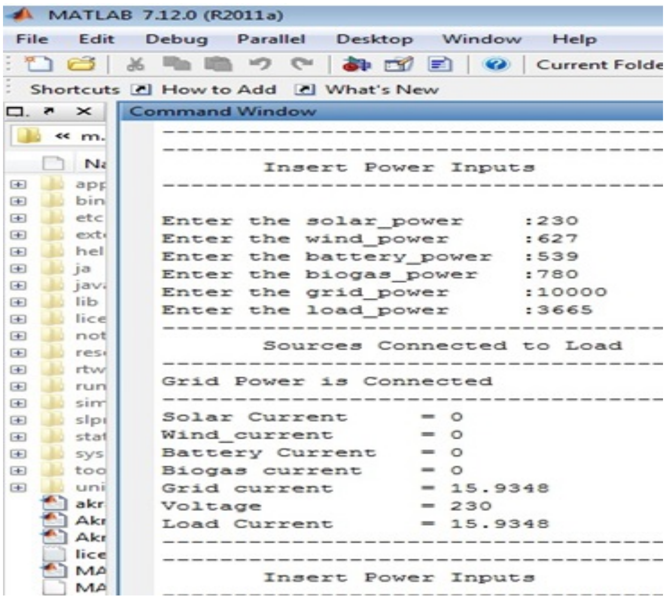

Fig 8. Grid power is serving load.

As illustrated in Fig. 7 biogas power is connected to the load. As solar, wind and battery powers are unable to fulfill the load demand and if biogas power is alone able to satisfy the load demand, then biogas power serves the load. The power available from solar (638W) and wind (1546W) is used to charge the battery. Still the grid power is not connected.

As in Fig. 8, grid power is connected to the load. If solar, wind, battery and biogas powers are unable to fulfill the load demand, then the last option is to use grid power to satisfy the load demand, hence grid power is serving the load. The power generated from solar (230W) and wind (627W) is used to charge the battery. Biogas developed from biomass is stored for future use.

6. Conclusion

The energy management for grid network of a distributed generation is presented. Operation of different sources with varied demands are tested and results are given. The energy management for efficient use of renewable energy sources is also introduced. It is also illustrated that the grid could be used only when renewable energy sources are not available due to some unforseen circumstances. The systamatic selection of renewable energy sources for different cases is sucessfully tested and results are presented. This study has established the necessary condition and preferences for optimum utilization helps in optimum use of the generation capacity of renewable energy sources without using the grid.

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