Grid Integration of Hybrid Energy System for Distribution Network

Atinkut Bayu[1], Degarege Anteneh[1]
and Baseem Khan[2,*]

[1]*Department of Electrical and Computer Engineering, Debre Berhan University, Ethiopia*
[2]*Department of Electrical and Computer Engineering, Hawassa University, Ethiopia*
E-mail: baseem.khan04@gmail.com
[*]*Corresponding Author*

Received 25 June 2021; Accepted 10 November 2021;
Publication 07 December 2021

Abstract

In the real world, most countries generate electricity from fuel, which has its own disadvantages. To minimize the usage of fuels, economic, social and environmental effects should be studied and focus should be given on the development of alternative power sources, such as solar photovoltaic (PV), wind energy, micro-hydro power and others. This paper focuses on the use of solar photovoltaic generation in conjunction with wind turbines to generate electrical energy. Further, this work studies the hybrid electrical energy generation system for the selected power network for Debre Berhan City. The developed hybrid system is connected to the grid to supply the load. Modeling of the power network and the components of the hybrid power network is performed by using MATLAB software. Results show the outputs of wind and solar PV generation are 168.5 kW and 173.3 kW, respectively, to supply the demand of 200 kW. Therefore, the most suitable option to supply

Distributed Generation & Alternative Energy Journal, Vol. 37_3, 537–556.
doi: 10.13052/dgaej2156-3306.3738

the demand is the combination of solar PV and wind turbines, which produces 357.8 kW.

Keywords: Hybrid energy system, distribution network, grid integration.

1 Introduction

Solar PV and wind turbine integrated hybrid power systems are becoming very vital due to their abundance, obtainability, and ease of harnessing energy for electrical power generation. In most parts of Ethiopia, power generation can be possible by using either solar PV or wind turbines, or a combination of both. Therefore, areas should be identified for the generation of electrical energy through solar and wind resources [1]. Electrical energy in Ethiopia is mainly generated from hydro (around 80%) as compared to other types of energy like wind, solar, and biomass. This makes the system unreliable, as atmospheric factors affect the power generation from hydro plants. Usage of renewable energy sources for electrical energy generation has a positive impact on the system reliability and socioeconomic growth of the community and has no adverse effect on the environment [2]. Figure 1 presents the schematic diagram of a hybrid renewable energy system integrated into the grid network. This research paper focuses on solar PV with wind turbines to develop a hybrid power system that generates and supplies electrical energy to the end user when the grid power from the utility is not enough to cover the load of the customer for different reasons.

1.1 Background Study and Related Work

Many researchers have developed hybrid renewable energy systems for the purpose of electricity generation. A hybrid renewable energy system generates more reliable electrical energy, as the single source of intermittent nature can't supply continuous generation. A hybrid system also provides an economical solution as many investigations have been conducted to decide the feasibility and benefits of the alternative energy sources tied to the power network. In [3], the design and optimization of a solar PV system is presented by utilizing a case study of KIOT administration offices. The paper deals with a standalone system consisting of solar power with a standby generator, battery banks, and power conditioning units to supply the KIOT administration building. Modeling and simulation of a standalone PV electric power supply system was done by HOMER software. Further, cost benefit analysis is also performed. In [4], modeling of wind turbines and photovoltaic systems is performed to illustrate the productivity and consistency, in order to increase production of power from the integrated network. The paper performed the modeling of each part of the solar PV and wind turbine systems and combined the two systems for comparing output voltage and power variation by using MATLAB Simulink. The paper demonstrates the efficiency of the modeled hybrid power system and concluded that the hybrid system can generate the maximum power for the moist summer weather compared to the individual case. In [5], simulation and control of a solar and wind hybrid renewable power system are performed. The authors modeled the combination of the solar and wind power supply to provide a meaningful combination of the two energy sources to get adequate electrical power from the renewable energy sources. The paper shows that the integration of these energy sources can increase the system generation capacity as compared to the individual operation of each energy source. Further, this paper demonstrates the photovoltaic optimum size along with the battery capacity and offers mitigation of discontinuity of wind power during low wind speed. In [6], modeling and simulation of a hybrid microgrid system is performed by employing a diesel generator, PV, wind, and fuel cell. Modeling, simulation and output analysis of solar power along with the system components are done in MATLAB software. For continuity of power during scarcity of renewable energy sources, diesel generators operate and supply electrical energy to the system. In [7], modeling, simulation, and management of the grid-integrated PV system with wind turbine combination have been studied. The combination of solar and wind supplies electrical power to the system, tied to the load of the power network. Ref. [8] performs the design, simulation, and management of a network integrated with solar and wind. By applying the maximum power point tracking system to solar power and using a synchronous generator for wind power, the required amount of electrical energy is obtained from the modeled system. The combination of generated electrical energy delivered to load buses. The economic functioning of the integration of the power network into the hybrid system is done in [9]. Different circumstances and evaluations of the integration of alternative energy sources for designing, management, and affordability of their costs are considered. In [10], modeling and simulation of solar PV and double feed induction generator-based wind turbines is performed. The paper modeled the hybrid of solar and wind power. For the maximization of the output power, the MPPT technique is utilized for solar systems. Further, enhanced DC voltage from solar is obtained by using a boost converter. Moreover, modeling of the back-to-back converter is performed for controlling wind power generation. Table 1 shows the comparative analysis of the existing literature.

Table 1 Comparative analysis of the existing literature

S No.	Reference	Applied Technique	Merits	Demerits
1	[5]	Simulation and Control of Solar Wind Hybrid Renewable Power System by using Matlab Software	Many simulation output analyses are done by considering different cases. Such as Case 1: PI voltage regulated inverter Case 2: fuzzy logic voltage regulated inverter	Do not consider the Cost of the system. Since the modeling system uses so many components, the cost of the modeling system may be high.
2	[6]	MATLAB Software is used to model and simulate a hybrid microgrid system comprised of solar, wind, fuel cells, and diesel generators.	The proposed model is simulated at temperature and variable irradiance in order to determine the system efficiency.	A diesel generator can be utilized as a standalone, emergency, or standby unit. This may lead to environmental pollution effects.
3	[7]	By using MATLAB software modeling, the hybrid system consists of two photovoltaic (PV) stations placed at different locations and one wind farm that are integrated into the main AC bus and supply the large plant with critical variable loads.	Using an MPPT control strategy based on measurement of mechanical power is applied to wind farms to capture the maximum power under changes in wind speed.	The system is costly since the control strategy needs more components.
4	[12]	Design & Implementation of PV Energy Systems for Electrification of Rural Areas	The load demand of the given customer is clearly specified and modeled.	The cost of system implementation may be higher.

(*Continued*)

Table 1 Continued

S No.	Reference	Applied Technique	Merits	Demerits
5	[16]	HOMER ENERGY software was used to design and simulate an optimal mini-grid Solar-Diesel hybrid power generation system in a remote Bangladesh to meet electrical energy demands in a reliable manner.	The optimal size of the photovoltaic (PV) panel, inverter, rectifier, and battery with a fixed capacity diesel generator, electrical load with a certain random variability, fraction of renewable electricity, excess electricity, and net present cost are calculated. The performance of different components in this system, electrical demand, fuel summary, emissions, and economic aspects are also analyzed.	Cost of the overall system is high

1.2 Research Gap

After detailed and critically analyzed the various researches, different techniques are missing to incorporate the following issues:

- Various literatures did not utilize the practical system implementation of the proposed work.
- Different literatures didn't utilize the practical data for the modeling of adopted system, while this work utilized the actual practical data.

1.3 Contribution of the Work

This work involves the design and simulation of a hybrid power network for Debre Berhan City using MATLAB. It provides results which can be used

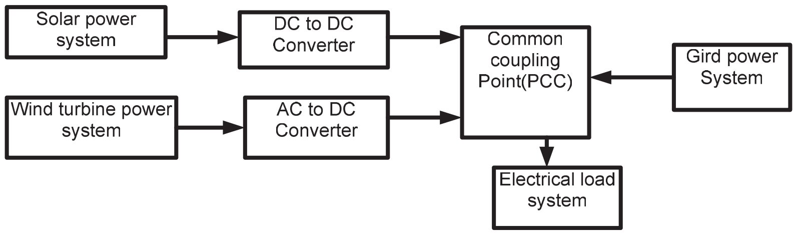

Figure 1 Hybrid Renewable energy system integrated to grid network.

for the planning of the future Debre Berhan city, to deliver electric power for customers from distributed generation and to reduce customers' dependence on the grid system and also to save utility from power loss. The following are the major contributions of this paper:

- Feasibility study and assessment of both solar and wind power sources
- The design of both solar and wind energy systems
- Solar, wind, and hybrid energy system modeling, simulation, and output analysis
- Providing customers with dependable power by reducing line loss and outage power
- Solar, wind, and hybrid power system results are compared.

2 Methodology

The methodology used to design and study solar PV with wind turbines in a hybrid electrical power network for the city of Debre Berhan. Modeling and simulation of the proposed system in MATLAB software is done, based on the mathematical analysis of the system parameters after the collection of the solar and wind data from the Debre Berhan meteorology agency as well as NASA. Wind speed, solar PV energy, and other necessary data such as temperature, are considered during modeling of the system. The optimized wind turbine model and PV array model are selected to obtain the power generated from these energy sources, and then evaluation of the hybrid, wind and solar power network on the basis of output nature is done.

2.1 Solar PV System Modeling

The electrical circuit of the solar photovoltaic system is shown in Figure 2. The circuit consists of solar modules to form the entire solar photovoltaic

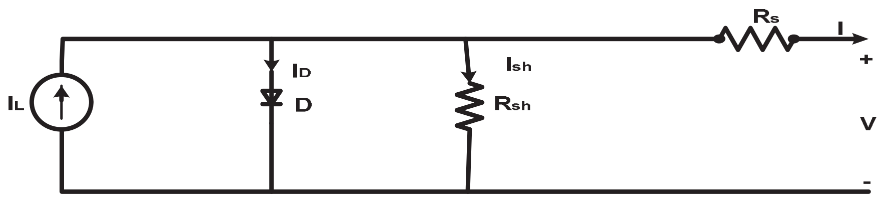

Figure 2 Electrical circuit diagram of solar photovoltaic module.

array. In order to get the desired amount of voltage from the solar photovoltaic system, the solar modules are connected in series, or to get the required amount of current, the modules are connected by means of a parallel connection. The connection type and the number of solar modules are determined based on the desired power output from the solar PV system [2].

Based on the voltage and current behavior of Figure 2, output current is calculated as follows:

$$I_{out} = I_L - I_{sat}\left[e^{\left[\frac{Q(V+IR_s)}{nKT}\right]} - 1\right] - \frac{V_t + IR_s}{R_{sh}} \tag{1}$$

where, I_L represents current produced from solar energy, I_{sat} is saturation current, Q is charge constant value such as 1.6×10^{-19}C, K has value of 1.38×10^{-23}J, T stands for ambient temperature of the system, R_{sh} and R_s represents shunt and series value of the resistances respectively. *n* is the ideal factor. By considering these solar cell parameters from Equation (1), the power supply from the solar PV system is obtained from Equation (2).

$$P_{module} = \frac{V_{OC} - I_n(V_{OC} + 0.72)}{1 + V_{OC}}\left[1 - \frac{R_s}{V_{OC}/I_{sc}}\right] * \frac{V_{OC1}}{1 + \beta I_n G_o/G} * \left[\frac{T_o}{T_1}\right]^{\gamma} * I_{SCO}\left[\frac{G_1}{G_o}\right]^{\alpha} \tag{2}$$

where, α indicates nonlinear characteristics of the solar current, β indicates solar module technology, γ indicates the effect of temperature in system voltage. G_0 indicates the normal solar radiation, G_1 indicates solar radiation in the case study area, and T_O and T_1 are the initial and final temperature of the solar module system. By accounting different factors [2], the electrical power supply by solar PV array is obtained from the Equation (3).

$$P_{pv} = N_p * N_s * P_{module} * \eta_{overall} \tag{3}$$

where, $\eta_{aoverall}$ represents the system overall efficiency and includes the maximum power point tracking wastage due to electrical parameters and dusts in the system [11]. N_p and N_s are represents the amount of solar modules aligned in parallel and series respectively. P_{pv} stands for power supply by the system.

2.1.1 Determination of total PV solar panel size

The total load is 200 kW. In order to get the solar array size required for the energy demand, the daily energy consumption in the form of kWh is determined. Given that the maximum number of sun hours in the study area is 4.3 hours, the overall efficiency of the solar panel is 0.6538. The total energy consumption (kWh) and the maximum power generated from the solar PV system can be obtained by Equations (4) and (5), respectively.

$$EC = Maximum\ demand(kW) \times 24\ hrs \tag{4}$$

where, EC represents total energy consumption per day.

$$P_{max}\,Generated(kW)from\ solar\ PV\ system = \frac{Total\ energy\ consumption\ per\ day(kWh)}{Peak\ Sun - \frac{hours}{day} * overall\ efficency} \tag{5}$$

where, P_{max} represents the maximum power generated. The PV system consists of strings of modules aligned in parallel, every string also made from series connected modules. The selected block for this work is the Monocrystalline module (Sun Power SPR-415E-WHT-D) taken from the Sun Power institution. The selected module contains 128 cells, supplies a maximum power of 415 W, the open circuit voltage is 85.3 V, and the short circuit current is 6.09 A. At its maximum efficiency, the voltage is 72.9 V, and the current is 5.69 A.

The power supply from the solar PV system must be equal to 1707.37 kW in order to supply the load of the system. Therefore, the required number of modules is obtained from Equation (6) as follows [12]:

$$The\ number\ of\ modules(Npv) = \frac{The\ needed\ power}{Maximum\ power\ of\ the\ panel} \tag{6}$$

The DC link capacitor voltage is determined to 650 V, and then the required amount of the PV modules is series connection calculated by using

Table 2 Results of PV sizing by using analytical

Parameters	EC	P (Max Array Output)	V_{MPV}	I_{MPV}	P_{dc}	V_{OC}	N_{PV}	N_{PVs}	N_{PVst}	I_{sh}
Values	4800	1770.27	656.1	2606.02	1709.8	767.7	4114	9	458	2789.32
Units	kWh	kW	V	A	KW	VDC	Module	Module	strings	A

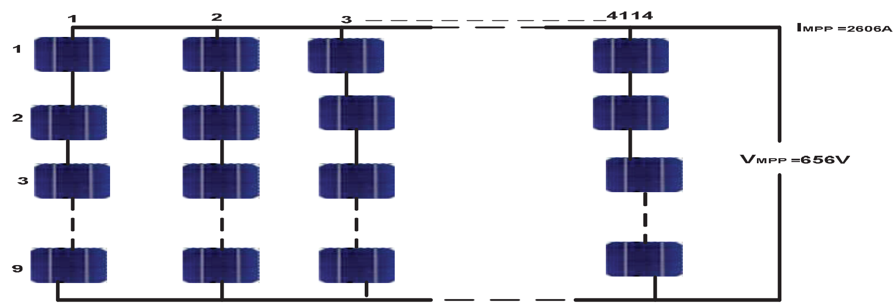

Figure 3 The solar network arrangement.

Equation (7).

$$N_{PVs} = \frac{DC\ nominal\ voltage}{Maximum\ power\ point\ voltage} \tag{7}$$

The quantity of strings required in the solar powered system is calculated by using Equation (8) [12]:

$$N_{PVst} = \frac{Number\ of\ array\ modules}{Number\ of\ PV\ series\ modules} \tag{8}$$

The results from Table 2 to generate 1707.35 kW of power at standard test conditions, 4114 solar modules, which has maximum power supply of 415 W, module with maximum power of 415 W is selected and arranged in 9 series modules and 458 parallel strings as illustrated in Figure 3 [18].

Power, voltage and current required by the system are obtained by using the following expressions.

$$V_{total} = N_s * V_{max} \tag{9}$$

$$I_{total} = N_p * I_{max} \tag{10}$$

$$P_{dc} = Vmpv * Impv \tag{11}$$

Open circuit voltage and short circuit current calculated by using Equations (12) and (13)

$$V_{OC} = Number\ of\ series\ modules * Open\ circuit\ voltage \quad (12)$$

$$I_{sh} = Number\ of\ parallel\ strings *\ Short\ circuit\ current \quad (13)$$

2.2 Wind Turbine Modeling

In order to get optimum electrical power from the wind speed, it must be high enough to rotate the wind turbine. According to the observation, there was regular wind speed in the area between the intervals of (4–9) ms^{-1}. These wind values are enough to generate electricity in the area [13]. The power supplied by the wind turbine power system is expressed as follows [14]:

$$P_{wind} = 0.5C_e\rho AV^3 \quad (14)$$

where, P_{wind} represents the output power from the wind turbine, C_e is the ratio between the gross power and the net power in the turbine blade and its maximum value is 59%. V represents the wind speed (i.e. 8 m/s utilized in this work), ρ stands for the air density of the study area (approximately 1.225 kg/m^3). A represents the area, equal to 1080.94 m^2.

2.3 Hybrid System of Solar PV-Wind Turbine

The supplied power from the combination of solar and wind power systems is obtained by adding the contribution from each source and is obtained by using Equation (15);

$$P_{tot} = P_{PV} + P_{wind} \quad (15)$$

where, P_{tot} represents power supplied by combining two sources together, P_{pv} denotes for power supply from solar photovoltaic system, P_{wind}, represents power obtained from wind power system.

3 Feasibility Assessment of Renewable Recourse for Debre Berhan City

Debre Berhan city is situated in the Amhara region, located at 9041°N latitude and 39031°E longitude, 130 km from Addis Ababa and the district of Debre Berhan Zuria. The Debre-Berhan town distribution system has started to be electrified since 1969 by the mini-hydro power of Abogedam, which is found to the north of the river Veresa, and by diesel sources. Even if Debre Berhan city is electrified early, the system's reliability is low, with high power outages every year [15]. Therefore, to solve the reliability issue, this work developed the hybrid renewable energy system.

Based on the assessment and data from the meteorology agency in Debre Berhan district and NASA, solar radiation as well as wind speed data for the study area is enough to generate power. However, neither the utility nor the customers used such abundant power sources during power outages and shortages.

3.1 Electrical Load Assessment in Debre Berhan

Electrical power can be used in the area for diverse purposes, including cooking foods (stoves and boilers), lighting in the class rooms, dormitories, clinics, street lights, powering computers and stationery machines, laboratory and workshop work, and other different purposes. The power consumption of the study area, with an addition of 10% for time-varying factors for different days, is computed. The estimated power required in this study is 200 kW, with an energy consumption of 4,800 kWh/day.

3.2 Solar Energy Assessment

Solar irradiation data for Debre Berhan is obtained from the National Renewable Energy Lab Database. Daily radiation in Debre Berhan was found to be between 4.2 kWh/m^2 and 5.8 kWh/m^2 per day. The mean value of solar radiation data throughout the year is 5.23 kWh/m^2/day. Irradiance values are enough to generate maximum power in the interval from January to May, while minimum values occur in the months of June to September. Solar irradiance data for the study area is shown in Table 3, which is collected from the meteorology agency.

From Figures 4(a) and 4(b), it is clear that a solar module's short circuit current is determined by the output of the sun's radiation strength. On the other hand, temperature affects open circuit voltage. Based on the variation of solar radiation and temperature, to get the required amount of power, a maximum power point tracking technique is utilized.

3.3 Wind Potential Assessment

Data collected from NASA and modeling of wind speed data for Debre Berhan at the height of 30 m are performed in MATLAB/Simulink software.

Table 3 Daily radiation in Debre Berhan (kWh/m^2/day)

Months	Flat kWh/m^2/day
January	5.833333
February	5.733333
March	6.333333
April	6.033333
May	6.333333
June	5.4
July	4.8
August	4.833333
September	5.3
October	6.633333
November	6.2
December	5.866667

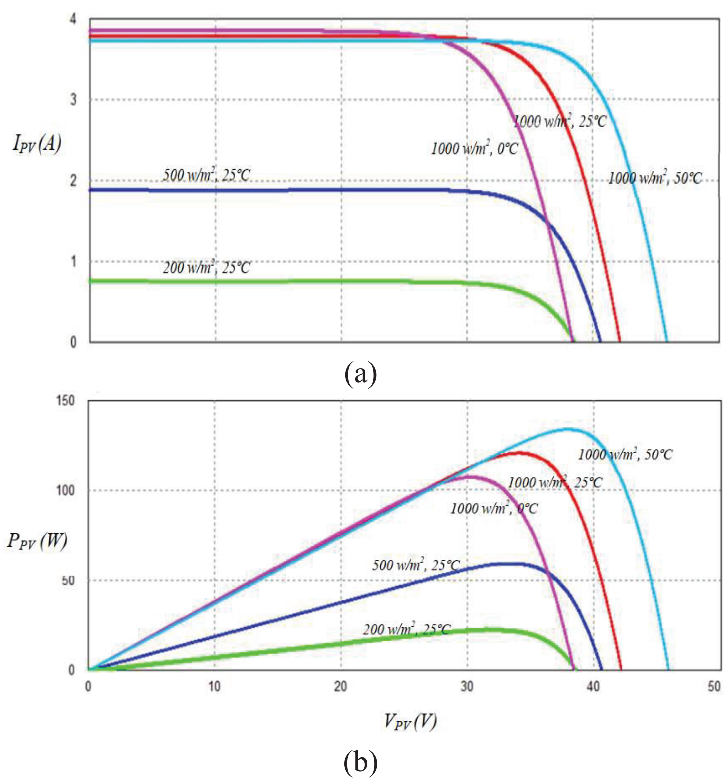

Figure 4 Photovoltaic (a) current (b) power behavior with variation of radiation as well as temperature.

Table 4 Climate and Weather Averages in Debre Berhan.

Months	High Temp	Low Temp	Mean Temp	Humidity	Wind Speed (m/s) At 30 m High
January	23°C	10°C	16°C	52%	6.734
February	25 °C	11 °C	18 °C	47%	7.2
March	25 °C	12 °C	19 °C	46%	6.734
April	25 °C	13 °C	19 °C	54%	6.25
May	25 °C	13 °C	19 °C	55%	5.77
June	23 °C	13 °C	18 °C	66%	4.8
July	21 °C	12 °C	17 °C	77%	4.8
August	21 °C	12 °C	16 °C	79%	4.8
September	22 °C	12 °C	17 °C	72%	4.8
October	23 °C	11 °C	17 °C	55%	6.734
November	23 °C	10 °C	16 °C	55%	6.734
December	23°C	9 °C	16 °C	54%	6.25

Wind speeds were found in the range of between 4.888 m/s and 9 m/s. Debre Berhan's wind speed and frequency distribution is illustrated in Table 3. This wind speed frequency has average values of between 4 and 9 m/s.

Therefore, these values are applicable to electricity generation [16]. Since the mean annual wind speed at Debre Berhan is above 4 m/s, which is quite enough for electricity generation, it is feasible to operate a wind turbine efficiently and economically. The calmer time of year lasts for 4 months, from June to September. In Debre Berhan, the higher wind speed occurs for the time interval of October to May, so in this time period, the mean wind speed is 6.25 m/s. On the other hand, the lower wind speed occurs in the time interval from June to September, with the lowest wind speed of 4.888 m/s.

3.4 Solar-Wind Hybrid Power Network

From the electrical energy demand data of the area, accessibility of renewable energy sources, with consideration of affordability of the appropriate grid connected solar and wind hybrid system is done in MATLAB/Simulink software. In the hybrid electrical energy generation system, power may be generated from either energy source or combination of the hybrid systems at any time, based on the availability of the energy sources in adequate quantity. In this work, the proposed system is integrated with the Ethiopian Electric Utility grid, and it is possible to supply power to loads even though both sources generate very little energy. Power supply from the hybrid renewable energy system is performed by the voltage converters.

3.4.1 DC link capacitor

The DC link capacitor for the proposed system has the main function of collecting electrical energy, which comes from the hybrid renewable energy system.

3.4.2 Inverter

Electrical power supply via the inverter, which transforms DC to AC electrical power and draws energy stored in the DC link capacitor. The electricity load supplied from the grid is of the AC type [17]. The inverter mathematical model for the PV and wind turbine is depicted below:

$$E_{PHYG-INV(t)} = E_{HYG(t)} * \eta_{INV} \tag{16}$$

where, $\mathrm{E_{PHYG-INV(t)}}$ represents energy output from inverter (kWh), $\mathrm{E_{HYG(t)}}$ represents Energy output from PV solar and wind turbine hybrid system (kWh), η_{INV} represents the inverter efficiency.

3.4.3 Controller

The controller compares the load bus voltage with its reference voltage, generates pulse signals with the help of PWM, and gives the signal to the inverter. An inverter circuit based on the response of the PWM generator converts the DC voltage from the DC link capacitor into an AC supply. By initiating IGBT Diode sinusoidal current drift, the inverter provides sinusoidal output within its characteristics and gives AC electrical power to the load bus. The inverter (IGBT-Diode) has been tied to the load bus as shown in Figure 5.

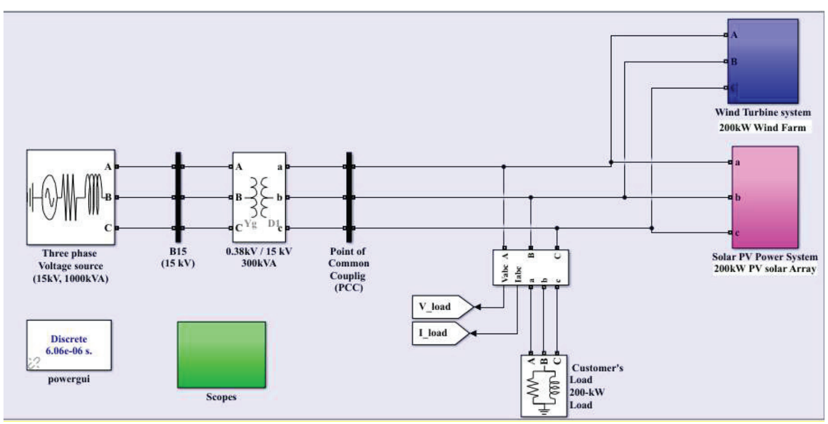

Figure 5 Hybrid energy system modeling using MATLAB/SIMULINK.

The entire system's MATLAB model, which consists of the 3-phase voltage source of the grid (15000 V), the transformer of the customer (15/0.38 kV), the wind turbine, and solar PV systems with their system components, is shown in Figure 5.

4 Simulation Results and Discussions

From the output of the system, it is observed that the wind turbine generates 168.5 kW. The power generated from wind turbines is not sufficient to balance electrical power demand in some cases, as shown in Figure 6. The solar PV power system produces 173.3 kW. This power is not enough to satisfy the load as illustrated in Figure 7.

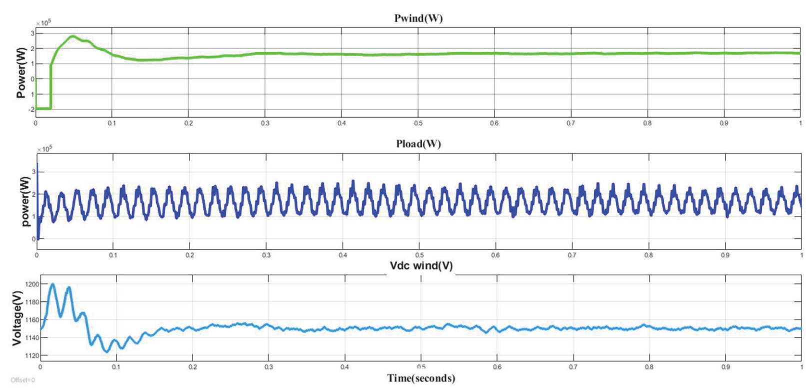

Figure 6 Simulation output of wind turbine system with loads.

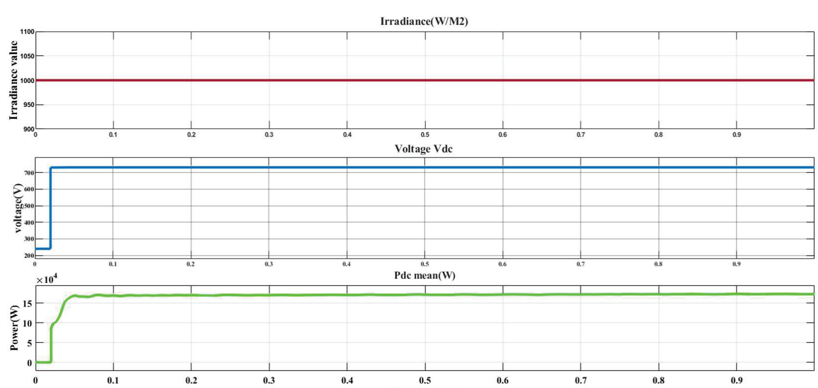

Figure 7 Simulation output of solar photovoltaic array system with loads.

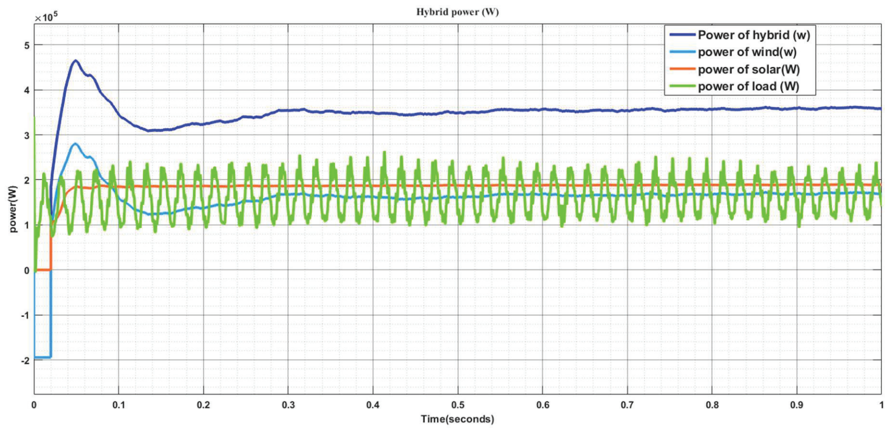

Figure 8 Simulation output of hybrid of wind turbine – Solar PV array system compare with loads.

Therefore, for the continuous supply of power to the load throughout the day, the best way is the power supply from a combined network of solar and wind turbines, which produce 357.8 kW to the load. This generated power, by considering the variations in solar radiation and wind speed throughout the day, is enough to satisfy the load as shown in Figure 8.

5 Conclusion

This paper focused on the solar-wind hybrid energy network design for the power network for Debre Berhan City. It is modeled and simulated in MATLAB/SIMULINK software. The demand required by the system is covered by using electrical energy produced by the hybrid solar and wind systems. This work considered the power demand of 200 kW, which is supplied by the hybrid system, which generated outputs of wind and solar PV generation are 168.5 kW and 173.3 kW, respectively. Therefore, the hybrid system can supply the power requirements of the system. Hence, it increases the reliability of the network. As a future enhancement of this work, the developed model can be utilized for the purpose of handling power quality issues of the network. Further, the controlling algorithms can also be utilized for advanced operation of the system.

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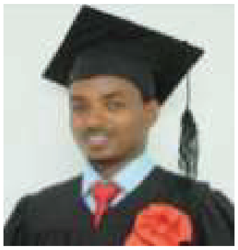
Biographies



Atinkut Bayu is with the department of Electrical and Computer Engineering, Debre Berhan University, Ethiopia. His research interest includes power system planning, power system reliability, renewable energy integration, renewable energy sources sizing and power quality.

Degarege Anteneh is with the department of Electrical and Computer Engineering, Debre Berhan University, Ethiopia. His research interest includes distribution network reconfiguration, wind energy generation, optimal renewable energy system integration techniques, power system planning, power system reliability, renewable energy integration, renewable energy sources sizing and power quality.

Baseem Khan (Senior Member, IEEE) received the B.Eng. degree in electrical engineering from Rajiv Gandhi Technological University, Bhopal, India, in 2008, and the M.Tech. and PhD degrees in electrical engineering from the Maulana Azad National Institute of Technology, Bhopal, in 2010 and 2014, respectively. He is currently working as a Faculty Member at Hawassa University, Ethiopia. His research interests include power system restructuring, power system planning, smart grid technologies, meta-heuristic optimization techniques, reliability analysis of renewable energy systems, power quality analysis, and renewable energy integration.