Potential and economic feasibility analysis of solar-biomass-based hybrid system for rural electrification

Harpreet Kaur Channi[1], Nimay Chandra Giri[2], Ramandeep Sandhu[3], Mohamed I. Abu El-Sebah[4], Fathy Abdelaziz Syam[4]
[1]Department of Electrical Engineering, Chandigarh University, Punjab, India
[2]Department of Electronics and Communication Engineering, Centurion University of Technology and Management, Odisha, India
[3]School of Computer Science and Engineering, Lovely Professional University, Punjab, India
[4]Department of Power Electronics and Energy Conversion, Electronics Research Institute, Cairo, Egypt

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ABSTRACT

A significant portion of the population lives in rural regions where the grid cannot provide them with enough power. Rising power demand, fossil fuel prices, limited fossil fuels such as coal, and environmental issues are the key drivers driving the usage of renewable energy resources for generating electricity. As a result, an alternate option for electricity generation in such remote places is required. Using renewable resources as alternatives would undoubtedly aid in mitigating the effects of global warming. The hybrid energy system combines electric power production with renewable sources such as solar, biomass, wind, biogas, hydro, and diesel generators (DGs). In light of this, a feasibility study on hybrid renewable energy was carried out for a specified remote region. This research investigates the efficacy of a solar-biomass-based hybrid power generation for rural electrification. The effective and sustainable alternative is found in a standalone hybrid version based on solar biomass. Electricity produced from the hybrid model proposed is $0.603.555 per unit, which is almost free of emissions of greenhouse gas (GHG), equally economical, and cleaner than the traditional supply. This system can be beneficial to electrify other adjacent remote zones.

Corresponding Author:

Fathy Abdelaziz Syam
Department of Power Electronics and Energy Conversion, Electronics Research Institute
Cairo, 12622, Egypt
Email: fathy@eri.sci.eg

1. INTRODUCTION

Rural electrification stands as a cornerstone of sustainable development, yet numerous remote communities worldwide still lack access to reliable electricity. In addressing this gap, renewable energy solutions have emerged as promising alternatives, offering clean and sustainable power and opportunities for socio-economic advancement. Among these solutions, solar-biomass-based hybrid systems have garnered attention for their potential to harness the complementary benefits of solar and biomass resources. This paper embarks on a journey to explore the feasibility and economic viability of implementing such a hybrid system for rural electrification within a specified rural area. By amalgamating solar energy's reliability with biomass's potential as a locally available and renewable resource, this hybrid approach presents a compelling case for sustainable energy provision in off-grid and underserved regions. Through a comprehensive analysis encompassing technical, economic, and social dimensions, this study seeks to shed light on the transformative potential of solar-biomass-based hybrid systems in driving rural electrification forward, ultimately contributing to the realization of sustainable development goals and the empowerment of rural communities worldwide. Interest in the worldwide switch to sustainable energy sources has increased due to global warming, rising carbon emissions, and the degradation of conventional energy sources. Power demands are on the rise, with the growing population and urbanization [1], [2]. A single source of renewable energy can only sometimes supply the energy demand. Hybrid systems thus become an essential choice [3]–[5].

Li *et al*. [6] investigated a West Chinese hamlet to prove the techno-economic feasibility of an off-grid hybrid renewable energy system (HRES) for distant rural electrification using modeling, optimization, and sensitivity analysis. Results demonstrate that a hybrid power system using solar, wind, and biomass is reliable and cost-effective for distant rural electrification with environmental advantages. An affordable power solution for society is achieved by improving hybrid energy system management, size, and component selection. Suresh *et al*. [7] used GA and HOMER pro software to minimize total net present cost (TNPC), cost of energy (COE), unmet load, and carbon dioxide (CO_2) emissions. Aberilla *et al*. [8] examined the life cycle environmental sustainability of diesel, solar, and wind-powered residential and community installations with battery storage. Six residential systems and 15 microgrids have been created and optimized for a typical Philippine rural community, including stand-alone and hybrid systems. Odou *et al*. [9] examined the techno-economic feasibility of a HRES for sustained rural electrification in Benin utilizing Fouay village as a case study. In conclusion, this hybrid photovoltaic (PV)/diesel generator (DG)/battery system can power distant locations because solar radiation is plentiful in Benin. It should be used for future electrification projects instead of the present extensively deployed PV/battery system. An optimization tool for a HRES is needed to discover the optimum capacity of diverse renewable energy supplies and help decision-makers investigate performance. Oladeji *et al*. [10] suggested a method that may be used to conduct feasibility studies and construct HRES for off-grid electrification, particularly in rural locations with restricted access to grid energy. In their study, Ullah *et al*. [11] devised a comprehensive decision-making methodology to effectively design a renewable energy supply system in a rural region of Pakistan. This system incorporates solar, wind, hydro, and biomass sources to generate 100% renewable energy. According to the findings, the solar-hydro-biomass battery is the highest-ranked off-grid system, with a life cycle cost of 10.9 million dollars. Araoye *et al*. [12] conducted a techno-economic evaluation of a hybrid microgrid system that combines diesel and biogas. When the biomass output reaches 4 tons or more, the hybrid system relies only on the biogas system to provide all of its energy. Sharma *et al*. [13] conducted research on power and voltage control in a self-sustaining hybrid microgrid system designed for distributing the electrical load. The research introduces a novel control technique that relies on autonomous solar, wind, and battery systems. Tay *et al*. [14] aimed to create an environmentally friendly and cost-effective hybrid power system. This system was designed to provide electricity to certain essential needs in the Avuto village of Ghana. The optimization computational findings indicate that the combination of system components, such as solar PV, wind turbine, and DG, is well-suited for the application location and has potential for future usage in rural and island electrification. The HRES comprises the battery, solar panel, and biomass generator. The system's efficiency is assessed and compared against HRES in many iterations, aiming to identify the configurations that provide the lowest net present cost (NPC) and COE values. Optimized solutions exhibit a commendable level of environmental efficiency, a desirable payback period, and reduced emissions [15], [16]. The research examines the computation of the incurred energy expenses to get the most economical generating system cost [17].

The scope includes evaluating solar irradiance and biomass availability, assessing energy demand, designing the hybrid system, analyzing technical compatibility and efficiency, estimating capital, and operational costs, calculating revenue streams, considering social and environmental impacts, reviewing policy frameworks, conducting risk analysis, engaging stakeholders, and making informed decisions [18]–[20]. The proposed methodaims to identify the best HRES designs concerning NPC and COE. The suggested upgraded HRES model must be economically advantageous, have significant environmental benefits, rapid payback time, and lower emissions. The following are the primary contributions of the proposed study:

– Determine the technical, economic, and social feasibility of deploying the hybrid system in the target rural area.
– Conduct a detailed economic analysis to assess the project's financial viability. This includes estimating capital investment requirements, operational costs, and potential revenue streams.
– Identify potential risks and uncertainties associated with the project and develop strategies to mitigate them.

The paper comprehensively investigates the potential and economic feasibility of implementing a solar-biomass-based hybrid system for rural electrification. In the introduction, the focus is on outlining the problem statement, emphasizing the need to assess the viability of integrating solar and biomass resources to meet the energy demands of rural communities. The methodology and system design section provides a detailed idea of suitable hybrid system design for electricity generation. In conclusion, the paper underscores the significance of addressing technical, economic, and risk-related aspects for informed decision-making, ultimately contributing to the advancement of sustainable rural electrification initiatives through the deployment of solar-biomass-based hybrid systems.

2. METHOD

The method for conducting the potential and economic feasibility analysis of a solar-biomass-based hybrid system for rural electrification involves a systematic approach encompassing several key steps. Initially, resource assessment is conducted to evaluate the availability of solar irradiance and biomass resources, utilizing on-site measurements and satellite imagery. Following this, energy demand analysis is undertaken, involving the collection of electricity consumption data or surveys to estimate the energy needs of the target community. Subsequently, system design and sizing aredetermined using software tools to setup optimized hybrid system, considering factors such as resource availability and energy demand fluctuations. Economic analysis is then performed, encompassing the estimation of capital investment, operational costs, and potential revenue streams, with financial metrics such as net present value (NPV) and payback period used to assess economic viability as shown in Figure 1. Sensitivity analysis evaluates the impact of key parameters on project economics, enhancing decision-making. Finally, findings are compiled into a comprehensive report, presenting recommendations to decision-makers and stakeholders, thereby guiding informed actions towards the implementation of the solar-biomass-based hybrid system for rural electrification. The data is obtained and provided in the following sections concerning the capacity for major usable sources of renewables (e.g., solar and biomass) at the proposed site. Whereas HOMER carries out an evaluation and optimization of the microgrid network before construction [21], [22]. The main objective goal of this project is to plan and construct a hybrid power source for a specified remote region using geographically available Goddard earth sciences (GES), specifically solar, biomass, and biogas. The data related to solar and biomass resources at the selected site have been collected from NASA and the Punjab Energy Development Agency (PEDA) [23]. The site visits and casual interviews of residents have also been performed in person and surveys of the technical solutions are available by consultation on a range of web pages for PV units, converters, and storage batteries.

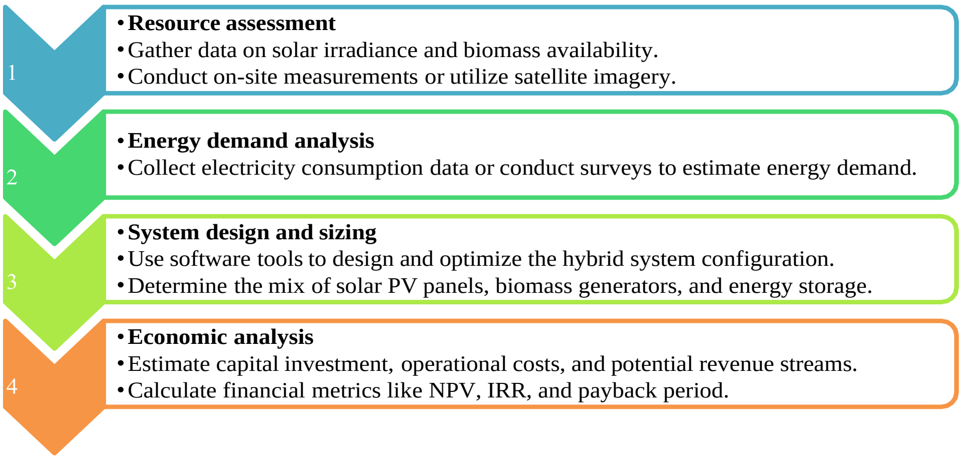

Figure 1. Method flow chart

3. SYSTEM DESIGN AND MODELLING

The hybrid model introduced would provide rural areas with energy stability. A hybrid power plant is a mix of multiple energy supplies (solar, wind, hydro, diesel, and biomass) with or without an energy supply system to satisfy the electricity demand. By providing electricity for agriculture's productive use, guaranteeing a sustainable energy environment, and relieving strain on traditional networks, the usage of these assets will reduce the need to transport power to rural regions and improve rural living. It is important to explore how current resources can be used to provide renewable energy to the rural area itself and to make the village viable in terms of its needs. In this study, optimization of solar PV-biomass is completed utilizing HOMER pro package to match the rural electricity demand of 770 households. The data in this work would enable the government and other major energy investors to create, prepare, and implement structure programs for rural electrification [24].

3.1. Resources of study area

For chosen research locations, NASA solar radiation data, surface meteorology, and solar energy websites are gathered [25]. Figure 2 indicates the average monthly solar radiation and clearness index. Figure 3 shows the biomass resources of the proposed system.

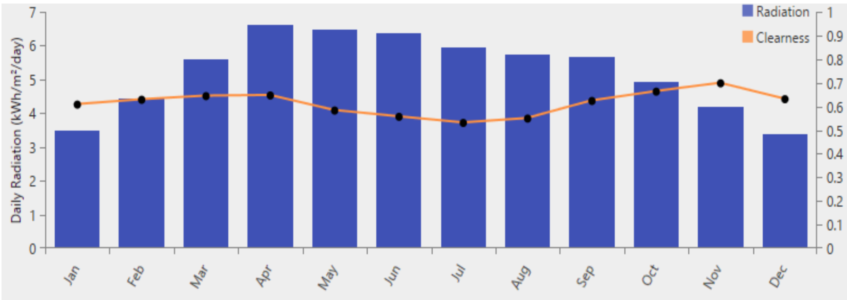

Figure 2. Monthly global horizontal irradiance data

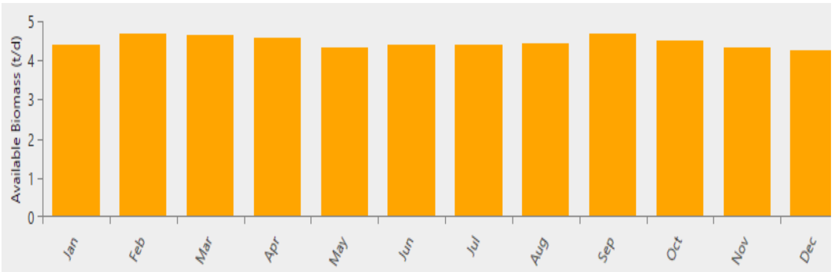

Figure 3. Monthly average available biomass data

3.2. The residential load of the village

Table 1 includes the total household load for a small village in the selected site, the number of appliances, their ratings, and the total load time. Figures 4 to 6 depict seasonal and yearly load profile patterns, with July acting as the peak month and December functioning as the off-peak month. The average daily energy consumption is 7.678 KWhr, and the average daily load is 2.651 KW.

Table 1. Calculations of the community's home electric load for 770 households

S. No	Gadget	Number in each House	Rating (W)	Total rating (W)	Utilization time (hours)	Load (KWh/day)
1	CFL	3	24	72	9	0.648
2	Ceiling fan	3	55	165	14	2.310
3	Water pump	1	750	750	1	0.75
4	Electric iron	1	1000	1000	1	1
5	Television	1	100	100	3	0.3
6	Washing machine	1	450	450	0.5	0.225
7	Refrigerator	1	150	150	24	3.600
Load for summer Total load in KW=2.615 Total load in KWhr/day=6.523				Load for winter Total load in KW=2.687 Total load in KWhr/day=8.833		
Average annual load=2.651 KW/day Average annual energy consumption=7.678 KWhr/day						

3.3. Simulation of hybrid solar photovoltaic-biomass model

Solar energy needs less maintenance but is limited to only 5-6 hours per day. Biomass energy has a dispatch capacity advantage, but annually, biomass prices vary on a wide scale. Solar PV biomass hybrid power station that will maximize the plant's efficiency by cosmbining its strengths and weaknesses. PV modules are one of the primary technologies used in the building of HRESs. The module is likewise expected to last 25 years. The load and the location of the sun determine the number of solar modules to be employed.

Structure and outside elements like solar radiation, wind speed, and ambient temperature have an impact on a PV panel's output power. Biomass fuels have the potential to be a viable alternative to conventional fuels. The incomplete burning of biomass produces combustible gases during the gasification process. A schematic of the HOMER Pro software-based hybrid solar PV-biomass model may be shown in Figure 7. With a peak demand of 2.39 kW, the scaled yearly energy consumption for the village load is 11.27 kWh/day. The PV system is connected to the direct current (DC) bus, while the biomass generator is connected to the alternate current (AC) bus. Both an inverter and a rectifier are employed by the converter. The battery is charged through a rectifier from the biomass generator when it is below DOD or 50%, and there is not enough solar energy.

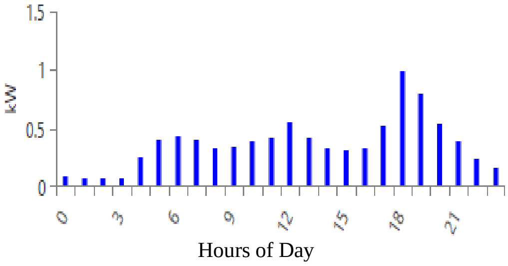

Figure 4. Daily load profile for a study area

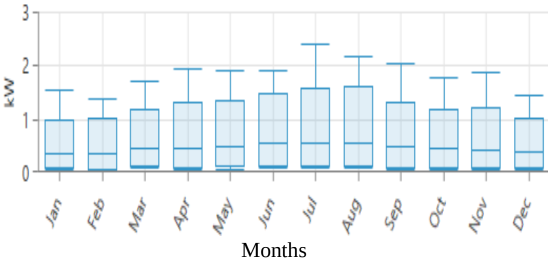

Figure 5. Monthly load profile for the study area

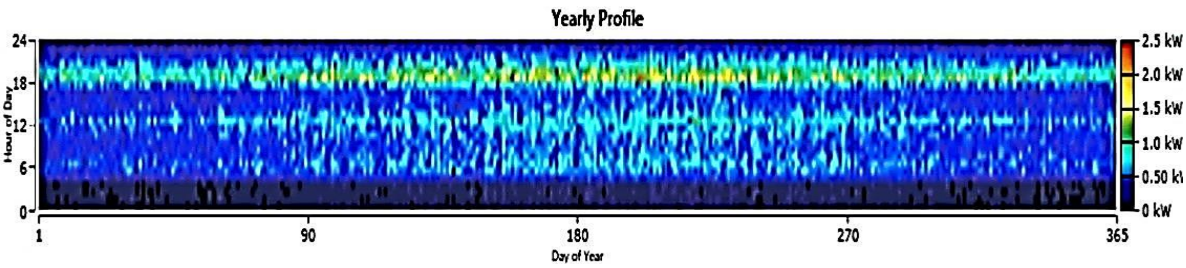

Figure 6. Yearly load profile for the selected area

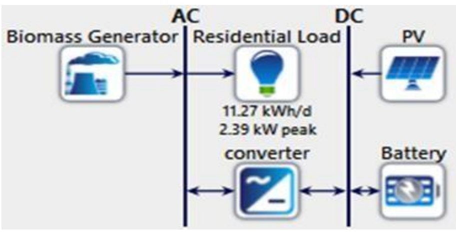

Figure 7. Schematic diagram of hybrid system design using HOMER software

4. RESULTS AND DISCUSSION

The results of the feasibility analysis indicate promising resource availability and an optimal system configuration for the solar-biomass-based hybrid system. Economic metrics such as NPV, internal rate of return (IRR), and payback period demonstrate favorable financial viability, supported by low operational costs compared to alternative energy sources. Mitigation strategies address potential risks, enhancing project resilience. Stakeholder engagement emerges as critical for community buy-in and long-term sustainability. Overall, the findings suggest that solar-biomass-based hybrid systems offer a feasible and economically viable solution for rural electrification. By leveraging renewable resources and engaging local communities, these systems can drive socio-economic development while contributing to environmental sustainability. Continued support for such initiatives is essential for realizing the transformative potential of renewable energy in off-grid and underserved areas, advancing global energy access goals, and fostering inclusive development. Depending on the availability of the energy supplies at the proposed location, the ideal strategy has been determined based on NPC, COE, and greenhouse gas (GHG) emissions. The term "net present cost" refers to the present value of all costs, including those for capital, replacement, operating, and maintenance, electricity costs, and so on (NPC). The term "energy cost" refers to the average price of each system unit (kWh) (COE). Table 2 also lists all technically and financially possible system configurations.

Table 2. Cost economies

Case	PV (kW)	Bio genration (kW)	Battery	Converter (kW)	NPC (US$)	COE (US$)	Operatingcost (US$/yr)	Initial capital cost (US$)	Renewable fraction (%)
1	2.095876	10	10	5	32091.27	0.603555	1226.189	16239.69	69.8
2		10	19	5	41665	0.783613	2163.215	13700	0
3	7.9375		28	5	45291.77	0.852542	1086.676	31243.75	100
4		10			74767.76	1.406192	5396.841	5000	0
5	6.65625	10		5	81211.13	1.527375	4375.976	24640.63	0

According to Table 2, five distinct examples are taken into account for analysis. The components of cases 1 through 4 are solar PV, a bio generator, a converter, and a battery. Cases 2 and 3 are made up of a bio generator, a converter, and a battery. The components of case 5 include solar PV, a bio generator, and a converter. With an NPC and COE of $32091.27 and $0.603555, case 1 of the solar PV biomass hybrid has the highest efficiency. It consists of a 2.095876 kW solar array, a 10-kW biomass generator, 10 lead-acid batteries, and a 5-kW converter.

Figure 8 indicates that most of the capital costs are contributed by SPV led by battery, biomass generator, and converter respectively. Batteries and converters are responsible for the maintenance costs since they must be changed over the life of the project. Compared to hydroelectric power, hybrids are deployable in wider areas. Overall, hybrids emerge as versatile, cost-effective solutions for rural electrification, aligning with sustainability goals and fostering resilience in off-grid communities.

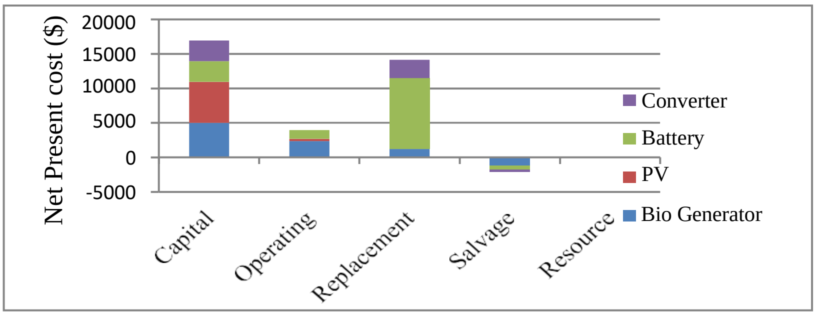

Figure 8. Net present cost summary

5. CONCLUSION

Solar-biomass-based hybrid systems offer a promising solution for rural electrification, balancing sustainability, reliability, and cost-effectiveness. With cleaner energy, resilience, and adaptability, they address the diverse needs of off-grid communities. To fulfill the energy needs of the 770 traditional homes in a residential area in the rural region of India, the research intends to develop and optimize HRES. Different HRES off-grid techniques reliant on accessible local resources were examined from a techno-economic-environmental perspective. The off-grid renewable energy setup has best results using PV and biomass sources. HRES s provide an effective solution to deliver electricity in outlying places. Using batteries, a biogas engine, and solar panels, a hybrid energy system for rural power was improved. In this paper, we examined the capacity of PV and biomass resources in a selected region in the Punjab Province. In this research work, a hybrid solar PV/biomass plant is modeled, simulated, and optimized for a small village in India. To serve the daily load requirement of the village the ideal system consists of a 2.1 kW PV, 10 kW biomass generator, 10 lead-acid batteries (12 V, 83.4 Ah), and a 5 kW converter. NPC and COE for the optimal system are $32091.27 and $0.603555. The hybrid configuration of the plant is $0.802637 cheaper than only the biomass plant with a payback period of 2.99 years. Thus, it is seen that the hybrid system is feasible and can deliver reliable power at lower rates with zero unmet loads. The proposed study can be extended to experimental applications for rural electrification.

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BIOGRAPHIES OF AUTHORS

Harpreet Kaur Channi is an Assistant Professor at Chandigarh University Mohali, Punjab. She received the B.Tech. in Electrical Engineering from BCET, Ludhiana and M.Tech. in Electrical Engineering from from GNE College Ludhiana, Punjab, India and Ph.D. from Chandigarh University Mohali, Punjab. She is Author of more than 26 Books. Editorial Board member of Various national and international bodies. More than 140 papers were indexed in Elsveir, Scopus, IEEE, Wos, and UGC. She is having 15 years rich experience in teaching and research. She can be contacted at email: harpreetchanni@yahoo.in.

Nimay Chandra Giri received B.Tech. in Electronics and Communication Engineering (ECE) at BPUT, Odisha, India, in 2010 and M. Tech in Communication Systems Engineering from CUTM, Odisha, India in 2014. He is currently serving as Assistant Professor, Department of Electronics and Communication Engineering and Center for Renewable Energy and Environment at CUTM, Odisha, India. He has 12.5 years of teaching, training, and skill experience. His research and skill areas include solar PV systems, energy conversion, protected cultivation, AVS, and aquavoltaic system. He can be contacted at email: girinimay1@gmail.com.

Ramandeep Sandhu is Assistant Professor at School of Computer Science and Engineering, Lovely Professional University, Punjab, India. She received B.Tech. and M.Tech. in Computer Science Engineering from GNE College Ludhiana, Punjab, India. She received Ph.D. in Computer Science Engineering from Lovely Professional University, Punjab, India. She has 14 years of teaching experience of reputed institutes. She has published 2 books. First one is named "OOPs Awareness with C++", ISBN: 978-93-5300-939-7. Another one is "A Start to C++ Programming with Object Oriented Concepts", ISBN: 978-93-955819-3-6. She can be contacted at email: ramandeepsandhu887@gmail.com.

Mohamed I. Abu El-Sebah is an Associate Professor at the Electronics Research Institute, Power Electronics and Energy Conversion Department, Egypt. He received B.S., M.S., and Ph.D. in Electrical Engineering from Cairo University in 1990, 1996, and 2003 respectively. Since graduating, he has been with the Electronics Research Institute (ERI) in Cairo, Egypt. In 2003, he became an Assistant Professor at ERI and Associated Professor Since 2016 at ERI. His research interests include electric drives, power electronics, and digital control. He can be contacted at email: mohamedibrahi32@eri.sci.eg.

Fathy Abdelaziz Syam is Assisstant Professor at Electronics Research Insitute, Power Electronics and Energy Conversion Depratment, Egypt. He holds a Ph.D. degree in electrical power and machines with specialization in Renewable Energy Systems from Cairo University in 2004, His research areas are solar energy, wind energy, microgrid, electrical machines, and power system. He can be contacted at email: fathy@eri.sci.eg.