CHEMICAL ENGINEERING TRANSACTIONS

VOL. 83, 2021

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-81-5; **ISSN** 2283-9216

DOI: 10.3303/CET2183095

Novel Designing Framework of Stand-alone and Grid-connected Hybrid Photovoltaic/Wind/Battery Renewable Energy System Considering Reliability, Cost and Emission Indices

Amirreza Naderipour[a], Zulkurnain Abdul-Malek[a], Shohreh Nasri[b], Saber Arabi Nowdeh[c], Hesam Kamyab[d,*], Shreeshivadasan Chelliapan[e], Mohd Wazir Bin Mustafa[f], Abdullah Asuhaimi Mohd Zin[f]

[a]Institute of High Voltage & High Current, School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru.
[b]Department of Electrical Engineering, Najaf Abad Branch, Islamic Azad University, Najaf Abad, Iran.
[c]Golestan Technical and Vocational Training Center, Gorgan, Iran.
[d]Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100, Kuala Lumpur, Malaysia.
[e]Engineering Department, Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
[f]School of Electrical Engineering, Universiti Teknologi Malaysia, Malaysia.
hesam_kamyab@yahoo.com

This paper novel multi-criteria designing framework of a grid-connected hybrid photovoltaic (PV)/wind turbine (WT) sustainable and clean energy system with battery (BA) storage (HPV/WT/BA) considering cost, reliability and emission costs are presented dependent on actual irradiance and wind speed patterns to include an annual load. The designing objective is optimal sizing of the HPV/WT/BA system to minimize the total net present cost (TNPC) as well as the loss of load and CO_2 emission cost with satisfying reliability constraint as energy not supplied probability (ENSP) considering stand-alone and grid-connected modes. The results showed that purchasing the power from network reduced the TNPC and also improved the hybrid system reliability and the reliability constraint is in the allowable range. The results also showed the superiority of the moth flame optimizer than the well-known particle swarm optimization (PSO) algorithm in achieving to lower TNPC and better reliability.

1. Introduction

Mandatory cessation of greenhouse gas emissions, air pollutants, industrial waste and sewage, and even the destruction of natural resources are seen as positive aspects of the spread of Covid-19 disease in the environment. Covid-19 pursued a set of limitations, including reducing travel, reducing non-essential purchases, stopping polluting industries, reducing forest and rangeland damage, and so on, all of which reduced air and nature pollution (Naderipour et al., 2020a). In the other hand in recent years, the use of sustainable energy has been growing (Kamyab et al., 2020). Different countries are trying to benefit from these resources due to their industrial applications and geographical location (Naderipour et al., 2019). Increasing the price of fossil fuels and the effects of these resources on the environment is also one of the reasons for the increase in countries' incentives to use sustainable energy (Kamyab et al., 2018). It makes a lot of sense to use distributed generation (DG) resources, especially based on sustainable energy sources, to provide the power needed by remote consumers over fossil power plants and to avoid spending cost on construction of transmission lines (Zin et al., 2016). One of the most important objectives of sustainable sources application is to reduce costs (Abdmouleh et al., 2017). The use of sustainable energy sources to

Paper Received: 05/09/2020; Revised: 12/11/2020; Accepted: 13/11/2020
Please cite this article as: Naderipour A., Abdul-Malek Z., Nasri S., Arabi Nowdeh S., Kamyab H., Chelliapan S., Mustafa M.W.B., Mohd Zin A.A., 2021, Novel Designing Framework of Stand-alone and Grid-connected Hybrid Photovoltaic/Wind/Battery Renewable Energy System Considering Reliability, Cost and Emission Indices, Chemical Engineering Transactions, 83, 565-570 DOI:10.3303/CET2183095

supply electricity to distributed and stand-alone loads in remote areas is a good way to reduce the economic costs of expanding and transmitting network lines, reducing environmental emission and increasing energy efficiency (Jahannoosh et al., 2020). In the hybrid systems, energy production fluctuations are controlled by using two or more sources of energy production and by storage systems, thus improving the reliability of the load (Hadidian-Moghaddam et al., 2018). The hybrid systems are used as stand-alone to provide remote loads from the power grid. Also, energy hybrid systems can be used in grid-connected mode (Naderipour et al., 2020b). This means that the main priority of the system is to supply the energy demand of the system and sometimes the excess power of the system is injected into the network (Rullo et al., 2019). When a hybrid energy system is based on PV and WT energy, an auxiliary energy source is needed to compensate for the fluctuations in the production capacity of these units due to changes in irradiance and wind speed (Jahannoush et al.,, 2020). Therefore, it is necessary to decide the size of the components optimally in order to achieve stable electricity in a hybrid system, as well as a compromise between energy output and consumption (Naderipour et al., 2020b). In addition, one of the major advantages of using hybrid energy systems is the reduction of environmental emission (Moghaddam et al., 2020). Environmental emission produced in the design and optimization of hybrid energy systems must be considered as an important factor (Jafar-Nowdeh et al., 2020). Therefore, minimizing the energy generation cost in this type of system as a function of the main goal, the optimal size of the system component to supply the load should be done by considering other indices such as emission cost and load loss penalty (Zin et al., 2016).
In this paper multi-criteria designing of stand-alone and grid-connected hybrid HPV/WT/BA system to minimize the total net present cost (TNPC) as well as the loss of load and CO_2 emission cost with satisfying reliability, the constraint is proposed to supply the annual load using moth flame optimizer and the results are compared with particle swarm optimization (PSO) algorithm.

2. Hybrid energy system

2.1 Page layout system configuration

The HPV/WT/BA sustainable energy system consists of PV, WT, battery (BA) and inverter to convert DC power to AC power according to Figure 1.

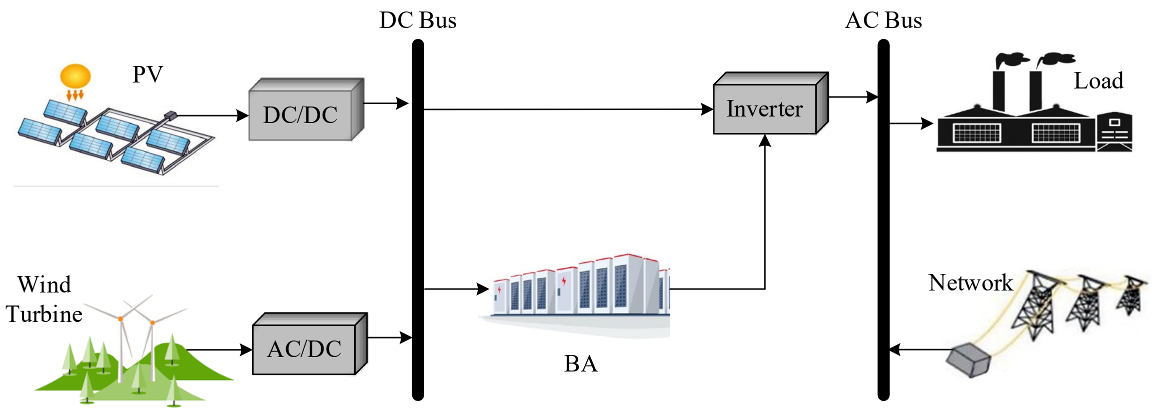

Figure 1: HPV/WT/BA sustainable energy system

2.2 PV model

The production power by photovoltaic (P_{PV}) is defined based on irradiance radiated to the PV surfaces as given by Eq(1) (Gharavi et al., 2015):

$$P_{PV} = \frac{(P_{PV,STC} \times E_{PV}) \times (Ir_V(t) \times \cos(\theta_{PV}) + Ir_H(t) \times \sin(\theta_{PV}))}{S_{STC}} \quad (1)$$

where, $S_V(t)$ and $S_H(t)$ refer to the horizontal and vertical component of irradiance, S_{STC} refers to standard conditions irradiance (1,000 W/m^2), θ_{PV} indicate PV installation angle (deg), E_{PV} is PV tracking efficiency and $P_{PV,STC}$ is PV nominal power (Hadidian-Moghaddam et al., 2016).

2.3 Wind Turbine model

The wind turbine output power based on wind speed (m/s) is defined in Eq(2) (Hadidian-Moghaddam et al., 2016).

$$P_{WT=}\begin{cases} 0 & ;Vw \le Vcutin, Vw \ge Vcutout \\ Pmwt \times \left(\frac{Vw-Vcutin}{Vr-Vcutin}\right)^m & ;\ Vcutin \le Vw \le Vr \\ Pmwt + \frac{Pcutout-Pmwt}{Vcutout-Vr} \times (Vw - Vr) & ;\ Vr \le Vw \le Vcutout \end{cases} \quad (2)$$

Here, P_{WT} represents the WT output power, Vw represents the wind speed, Vcutin represents the cut-in speed, Vr represents the nominal speed, $\mathrm{Vcutout}$ represents the cut-out speed, Pmwt represents the maximum power of the WT unit (kW), and $Pcutout$ represents the output power at the cut-out speed. At 40 m, the wind data is registered, and the height of the turbine is 15 m. In Eq(3), the wind speed at this altitude is determined (Hadidian-Moghaddam et al., 2016).

$$v_W^h = Vref \times \left(\frac{\mathrm{Hwt}}{HwtG_{ref}}\right)^{\mu} \quad (3)$$

Here, v_W^h represents the wind speed at Hwt, $Vref$ represents wind speed at Hwt_{ref}, and μ is exponent law coefficient that its range is from 0.14 to 0.25 (Hadidian-Moghaddam et al., 2016).

2.4 Battery model

The battery is used to compensate for fluctuations in the supply of renewable energy resource and improve load reliability (Hadidian-Moghaddam et al., 2016).
When the energy produced by the renewable energy sources at time *t* exceeds the load demand, the excess energy is transferred to the battery and stored. The energy stored in the battery at time *t* ($SOC_{Batt}(t)$) is given by the Eq(4).

$$SOC_{Batt}(t) = SOC_{Batt}(t-1) + \left[\left(P_{PV}(t) + P_{WT}(t)\right) - \frac{P_{oad}(t)}{\eta_{Inv}}\right].\Delta t \quad (4)$$

Here, $SOC_{Batt}(t)$ represents the stored energy in the battery at time *t*-1, $P_{oad}(t)$ represents the load demand at time *t*, η_{Inv} represents the inverter efficiency, and Δt represents the time step (1 h).
If the load exceeds the energy generated from the renewable sources, the battery is applied to compensate for the lack of load energy. The battery energy at time *t* is calculated by the Eq(5).

$$SOC_{Batt}(t) = SOC_{Batt}(t-1) - \left[\frac{P_{oad}(t)}{\eta_{Inv}} - \left(P_{PV}(t) + P_{WT}(t)\right)\right].\Delta t \quad (5)$$

2.5 Objective function

The objective function of designing the HPV/WT/BA system is defined by the Eq(6).

$$Min\, TNPC = NPC_{cap} + NPC_{main\&oper} + NPC_{rep} + NPC_{loss} + \Delta \times [\textstyle\sum_i CP(t) + \sum_m CD(mt) + NPC_{Emission} + NPC_{Emission} \quad (6)$$

Here, $TNPC$ represents the cost of the hybrid system over its lifespan, and NPC_{cap}, $NPC_{main\&oper}$, and NPC_{rep} represent the initial capital cost, maintenance and operation cost, and cost of replacing components, respectively. Here, *CP*(*t*) represents the cost of energy purchased from the network per hour, *CD*(*mt*) represents the price paid for the maximum power purchased per month.

2.6 Energy not supplied probability constraint

In this study, the energy not supplied probability (ENSP) is defined for reliability evaluation. The ENSP changes between 0 and 1 values in the Eq(7) (Ahmadi and Abedi, 2016).

$$ENSP = \frac{ENS}{\sum_{t=1}^{T}[P_L(t)]} = \frac{\sum_{t=1}^{T}[P_L(t) - (P_{PV}(t) + P_{WT}(t)) - SOC_{BA}(t)]}{\sum_{t=1}^{T}[P_L(t)]} \quad (7)$$

The reliability indices as reliability constraint are presented by the Eq(8).

$$ENSP \le ENSP^{max} \quad (8)$$

Where, $ENSP^{max}$ is the maximum value of $ENSP$.

3. Simulation results

The results of HPV/WT/BA system design for stand-alone and grid-connected mode are presented aimed at minimizing the TNPC and satisfying the ENSP reliability constraint based on the MFO, and the design results are compared with PSO method.

3.1 System data

The moth–flame optimization (MFO) is applied to design the HPV/WT/BA system aimed TNPC with satisfying the ENSP. The total load is 269 MWh for a year. In Figure 2-4, data of irradiance, wind speed, and load for a year are shown. The parameters of the hybrid system are presented in Table 1.

Table 1: Hybrid system parameters (Naderipour et al., 2020b)

Device	NPC_c (USD/unit)	NPC_r (USD/unit)	NPC_m (USD/unit)	Rated Capacity	Efficiency (%)	Lifetime (Year)
Wind	19,400	15,000	75	7.5kW	-	20
PV	7,000	6,000	20	1kW	-	20
Battery	750	700	7	1kW	85	10
Inverter	800	750	7	1kWh	90	15

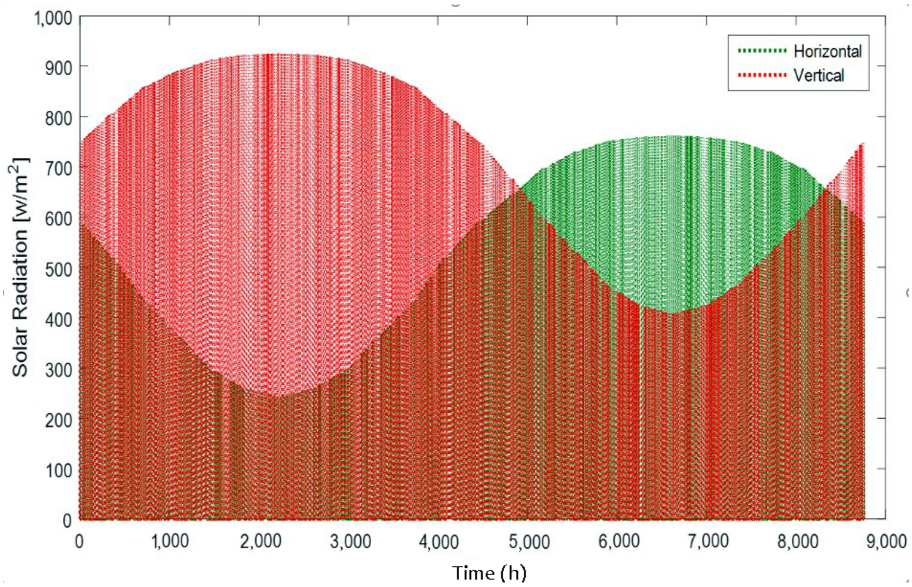

Figure 2: The horizontal and vertical solar irradiance during a year

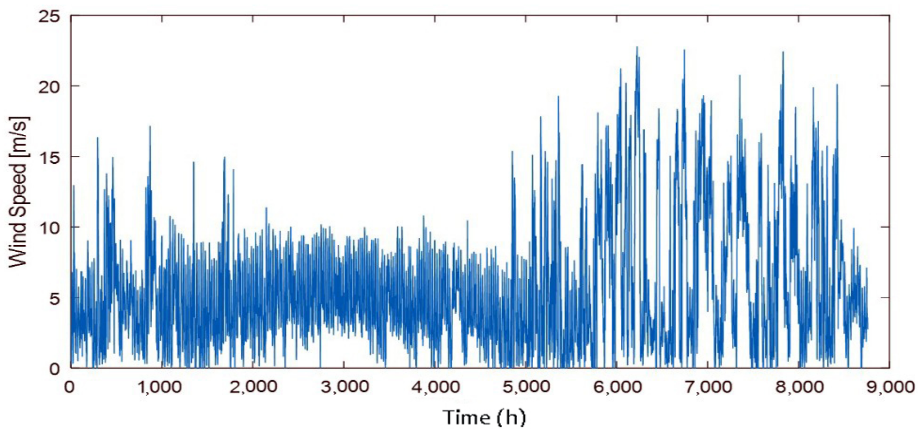

Figure 3: The wind speed during a year

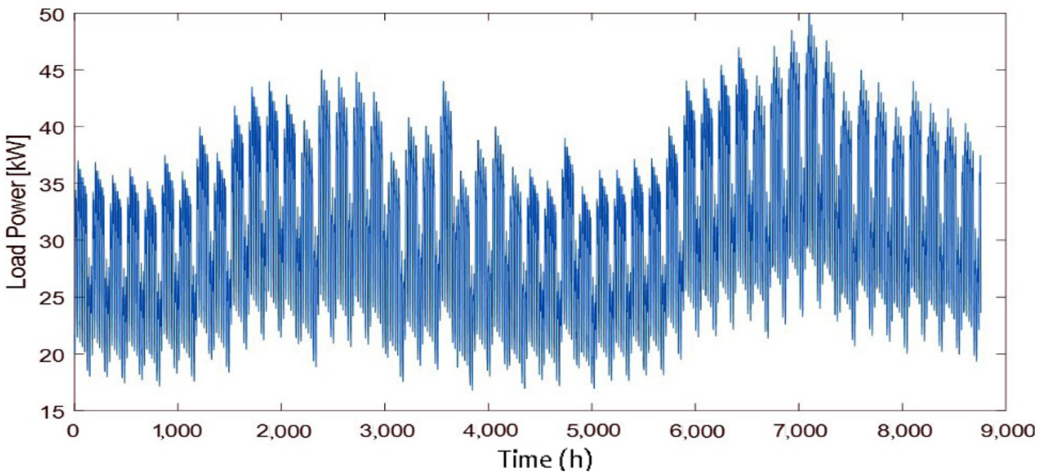

Figure 4: The load demand during a year

3.2 Stand-alone and Grid-connected mode results

The findings indicate (Table 2) that the procurement of electricity from the network decreased the TNPC and also increased the efficiency of the hybrid system and the limitation of reliability is within the permitted limit. The findings also revealed the supremacy of the moth flame optimizer in achieving lower TNPC and higher efficiency than the well-known PSO algorithm.

Table 2: Comparison the results of HPV/WT/BA system designing with previous studies

Parameter	N_{WG}	N_{PV}	N_{Batt}	P_{Inv} (kW)	θ_{PV} (deg)	$ENSP$ (%)	$TNPC$	COE	$NPC_{Emission}$	NPC_{net}
MFO (stand-alone)	8	128	144	47.84	35.92	0.0021	1.3077	0.2432	--	--
MFO (grid-connected)	8	127	144	47.91	35.44	0.0010	1.2946	0.2407	20,703	4,860
PSO (stand-alone) (Jahanbani et al., 2010)	14	115	69	47.62	37.36	0.0070	2.8025	0.5209	--	--

4. Conclusion

In this paper, the novel framework of optimal design of HPV/WT/BA Energy System is presented to minimize the TNPC costs, load loss cost, as well as emission, cost satisfying the reliability constraint as ENSP in stand-alone and grid-connected modes based on real irradiance and wind speed data. The amount of PVs, WTs, batteries, inverter power transmitted to the load and the angle of the PV panels that are optimally calculated using the MFO approach are the decision variables for the design problem. The results cleared that in grid-connected mode with purchasing the power from the network the TNPC can be reduced and also the reliability can be enhanced. The results also demonstrated the better capability of the MFO in optimal designing of the hybrid system with less cost and ENSP than the PSO algorithm.

Acknowledgement

This research was funded by the Universiti Teknologi Malaysia (Post-Doctoral Fellowship Scheme grant 05E09, RUG grants 4B482, 01M44, 02M18, 05G88) and Post-Doctoral fellow (Teaching & Learning) Scheme under MJIIT-UTM.

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