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Archimedes optimization algorithm based maximum power point tracker for wind energy generation system

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ABSTRACT

Improving the operation of wind energy generation system is a big challenge especially when it operates under unstable weather conditions. Therefore, installing a tracker for monitoring the maximum power expected to be generated from the wind energy system is essential, this controller is known as maximum power point tracker (MPPT). Hill climbing based approaches were applied for simulating the tracker, however they have limitations in tracking speed and efficiency. This paper proposes a recent efficient approach of Archimedes optimization algorithm (AOA) for simulating MPPT installed with the wind energy generation system. The constructed system composes wind turbine (WT) connected to a permanent magnet synchronous generator (PMSG), the AC output power from the generator is converted to DC via 3-phase rectifier, the DC voltage is the input of boost converter which is controlled via its MOSFET duty cycle. The designing process is presented as an optimization problem considering the electrical output power from the system as the target. The proposed AOA tunes the converter duty cycle to maximize the output power. Three scenarios are followed in this work which are fixed wind speed, variable wind speed, and real wind speed recorded at four sites in Saudi Arabia (Sakaka, Riyadh, Jeddah, and Jizan). The obtained results via the proposed approach are compared with the results obtained via cuckoo search (CS), grasshopper optimization algorithm (GOA), and electric charged particle optimization (ECPO). The results confirmed the robustness of the proposed AOA-MPPT in achieving the best performance of wind energy generation system.

1. Introduction

Due to the environmental concerns related to the usage of conventional energy generation sources, renewable energy sources (RESs) like solar and wind penetrated strongly in many engineering applications [1–3]. Among RESs, wind energy represents the most quickly developed source of energy [4,5]. In wind energy generation system, the electrical energy is generated from the mechanical power produced from wind turbine (WT) which is coupled to prime mover via a gear box. It causes the rotor of generator to move while the load is connected to the stator winding. The mechanical power from WT can be controlled in the specified range of wind speed, this range begins from the cut-in speed ($V_{cut\text{-}in}$) to the cut-out speed ($V_{cut\text{-}out}$). For wind speed out of the specified range, the prime mover shouldn't operate for safety purpose. WTs are classified based on constant or variable wind speed. However, the maximum power can be obtained only for turbines of variable wind speed. In such type of the turbine, it is required to install power converter to control the power flow, this controller is the maximum power point tracker (MPPT). In variable speed WTs, the rotational speed can be varied to be consistent with the wind speed variation. Therefore, they have a merit of preserving constant optimum tip speed ratio at which the maximum power is obtained. To extract the maximum power from WT, MPPT is essential. The algorithms employed in MPPT can be categorized to indirect and direct power controllers. The first one maximizes the mechanical power only without any control in electrical power

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while the second one controls directly the electrical output power. The direct power controller algorithms are hill climbing search (HCS) and incremental conductance (INC), these algorithms are sensorless that locate the maximum power point (MPP) via analyzing the power variation with the aid of predetermined curve. Perturb and observe (P&O) is considered as the commonly used HCS. However, these conventional control algorithms have some limitations in tracking speed and efficiency as they failed in extracting the MPP especially in case of rapid change in wind speed.

The rest of the paper is arranged as: Section 2 introduces the previous reported methods, Section 3 presents the detailed model of the wind energy based system, Section 4 introduces the main aspects of Archimedes optimization algorithm, Section 5 explains the proposed optimization formula, Section 6 introduces the results and discussion, and conclusions are given in Section 7.

2. Literature review

Great works were conducted in simulating the MPPT for wind energy generation system, most of them employed conventional algorithms like P&O and modified P&O while other researchers used metaheuristic optimization approaches to optimize either proportional integral (PI) controller or artificial neural network (ANN)-based controller.

Sitharthan et al. [6] presented a modified particle swarm optimizer (PSO) for simulating the MPPT for doubly fed induction generator fed via wind energy. The authors used neural network with radial basis function in addition to the modified optimizer. *Kumar et al.* [7] introduced a comparative study between two different approaches which are P&O and HCS for hybrid solar/wind system. A brushless power split transmission system has been introduced by *Luo et al.* [8] to drive the wind energy generation system, moreover a comparison with single MPPT was conducted. *Priyadarshi et al.* [9] used ant colony optimizer for simulating the MPPT used with a hybrid solar/wind system for enhancing its output power. Moreover, Fuzzy logic control (FLC) has been employed to control the inverter in comparison with the classical PI controller. Some problems accompanied to the operation of wind energy generation were vanished by employing new MPPT strategy based on adaptive active fault tolerant control [10]. *Ghoudelbourk et al.* [11] developed a fractional control methodology for tuning the pitch angle of the wind energy system for maximizing its generated power. Moreover, comparison to the PI and PI^{α} controllers has been conducted. *Kumar et al.* [12] reviewed many algorithms employed in simulating the MPPT for wind energy system with clarifying the merits and defects of each one. *Brasil et al.* [13] constructed a model of wind energy system installed in the grid, moreover FLC for MPPT was installed to maximize the system output power. *Fathabadi et al.* [14] presented a universal tracker for monitoring the peak power of hybrid fuel cell (FC) /photovoltaic (PV)/wind energy to enhance its performance. Three sensors are required for measuring the terminal voltages of three power sources without requiring more expensive sensors like anemometer and tachometer. Neural network with radial basis function was presented as control strategy for maximizing the power generated from the wind energy generation system [15]. Moreover, gradient descent algorithm was implemented for training the network while a modified PSO was used for implementing the learning process. *Zhi et al.* [16] used disturbance of rotational speed of wind energy system to establish a maximum power tracking approach of variable step size. *Kadri et al.* [17] reviewed two approaches of MPPT for wind energy system which are tip speed ratio and HCS. An approach based on field-oriented control has been presented by *Behjat et al.* [18] as MPPT for small scale wind energy generation system. An adaptive P&O based MPPT was used with variable speed wind energy system [19]. *Youssef et al.* [20] presented a self-adaptive P&O approach for MPPT incorporated with wind energy system to enhance its output power. A sensorless MPPT installed with an improved small scale wind energy system has been introduced in [21]. In such study, comparison with Fuzzy logic, variable, and fixed step P&O has been conducted. Adaptive P&O and hybrid P&O control methodologies for MPPT installed with wind energy system were presented in [22] to enhance the generated power. A variable step P&O based MPPT was presented to variable speed wind energy generation system [23]. *Hu et al.* [24] selected a slide mode extremum seeking control as MPPT installed with wind energy generation system. Moreover, an improved invasive weed optimizer has been introduced to optimize the parameters of the constructed controller. In [25], model predictive control (MPC) based MPPT was introduced to extract the maximum power of wind energy system. *Mokhtari et al.* [26] constructed MPPT for wind energy system using PI controller optimized via ant colony optimizer to enhance the tracking speed of the controller. A novel control on the basis of MPPT pitch angle constructed via neural network was employed to maximize the wind system output power [27]. Two MPPT approaches, tip speed ratio and optimum torque control, installed with wind energy system have been introduced in [28]. *Li et al.* [29] presented a hybrid approach combining HCS and power signal feedback control for simulating MPPT for wind energy system. PI controller optimized via PSO was presented by *Bekakra et al.* [30] as MPPT incorporated with doubly fed induction generator driven by WT. An adapted step size of HCS based tracker for wind energy system was conducted in [31]. *Wei et al.* [32] simulated MPPT for wind energy system using neural network with reinforcement learning. *Singaravel et al.* [33] introduced solar/wind energy connected to the grid with the aid of single boost converter followed by inverter. MPPT based on dsPIC30F4011 controller for extracting the maximum power from wind energy system was introduced in [34]. *Fathy et al.* [35] presented an approach based on grasshopper optimizer (GOA) for simulating MPPT installed with wind energy generation system in Aljouf region, Saudi Arabia. The GOA controlled the converter duty cycle such that the output power is enhanced. Different locations in Aljouf region were studied and the presented approach has been compared with other optimizers.

Despite the large number of reported methods used in simulating MPPT with wind energy system, the application of metaheuristic algorithms is still limited and need more attention especially after they confirmed great efficiency in obtaining the maximum power point (MPP) of photovoltaic system [36–41] and also with fuel cells [42–44]. Moreover, hill climbing search algorithms have some limitations in tracking speed and efficiency, moreover they may fail in extracting the MPP.

To cover the gap that exists due to the use of the previous methods, an efficient metaheuristic approach of Archimedes optimization algorithm (AOA) is proposed to design MPPT installed with PMSG driven by WT. AOA is characterized by its straightforward implementation, it requires less controlling parameters (population size and stopping criterion). Moreover, the convergence of AOA can be controlled via assigning random and adaptive parameters. Furthermore, it achieves balance between the exploration and exploitation phases that enables the approach to achieve the global optima.

The following points summarize the contribution of this work,

- It is the first time to propose Archimedes optimization algorithm (AOA) to design MPPT controller installed with wind energy generation system operated at different locations in Saudi Arabia.
- The proposed AOA is employed to tune the dc-dc boost converter duty cycle to maximize the output power from the wind energy system.

- The proposed approach based MPPT is investigated at different weather conditions at four regions in Saudi Arabia which are Sakaka, Riyadh, Jeddah, and Jizan.
- Comparison to cuckoo search (CS), grasshopper optimization algorithm (GOA), and electric charged particle optimization (ECPO) is conducted.
- The robustness and competence of the proposed AOA-MPPT controller is confirmed.

3. Wind energy system model

The construction of the wind energy generation system considered in this work is shown in Fig. 1. The system comprises WT connected to PMSG, the AC output power from the generator is converted to DC via 3-phase rectifier. The DC voltage and current are fed to the boost converter which is controlled via the proposed AOA-MPPT controller. Two inputs are fed to the proposed controller which are mechanical speed of WT which is measured by tachometer and the electrical power, the controller output is the duty cycle. The model of each component of the constructed wind energy generation system is explained as follows:

A. Wind turbine (WT) model

The wind turbine (WT) converts the wind power to mechanical one, the wind power can be expressed as follows [45]:

$$P_w = \frac{1}{2}\rho A V_w^3 \tag{1}$$

where ρ refers to the air density, A represents the cross-section area of WT, and V_w is the wind speed.

The mathematical formula of the mechanical power generated from WT can be written as follows [45]:

$$P_m = C_p(\lambda, \beta) P_w \tag{2}$$

where C_p represents the power coefficient, β refers to the pitch angle of WT, and λ is the ratio of tip speed.

The formula of C_p can be written as follows:

$$C_p = C_p(\lambda, 0) = C_p(\lambda) \tag{3}$$

The variation of C_p with λ at different WT pitch angles is shown in Fig. 2. The maximum power of each curve is defined by λ^{opt} and C_p^{max}.

The variation of WT mechanical power and the rotational speed is shown in Fig. 3, the rotational speed at the maximum mechanical power can be expressed as follows:

$$\omega_m^{opt} = \frac{\lambda^{opt} V_w}{R} \tag{4}$$

The WT maximum power is calculated as follows:

$$P_m^{max} = C_p(\lambda^{opt}) P_w = \frac{1}{2} C_p^{max} \rho A V_w^3 \tag{5}$$

B. Permanent magnet synchronous generator (PMSG) model

Many types of generators can be installed with WT like PMSG, doubly fed induction generator (DFIG), dual-stator IG, and optislip IG (OSIG) [46]. In the constructed system, PMSG is used as it is efficient and it doesn't require any gear box for connection [47]. The dq voltages of PMSG can be calculated as follows:

$$v_d = L_q \omega_e i_q - L_d \frac{di_d}{dt} - R_s i_d v_q = \sqrt{\frac{3}{2}} \Phi_{sf} \omega_e - L_d \omega_e i_d - L_q \frac{di_q}{dt} - R_s i_q \tag{7}$$

where L_d is the inductance of d-coil, L_q is the inductance of q-coil, R_s is the resistance of stator windings, i_d is the current in d-axis, i_q is the current in q-axis, ω_e is the angular frequency, and Φ_{sf} is the flux linkage produced by the permanent magnet of the rotor. The electromagnetic torque is given as follows:

$$T_L = P\left[\left(\sqrt{\frac{3}{2}}\right)\Phi_{sf} i_q + (L_q - L_d) i_d \times i_q\right] \tag{8}$$

where P is the pole pair number. The dynamic behavior of WT and PMSG can be written as follows:

$$T_m - P\left[\sqrt{\frac{3}{2}}\Phi_{sf} i_q + (L_q - L_d) i_d \times i_q\right] - f \times \omega_m = J\frac{d\omega_m}{dt} \tag{9}$$

where J is the inertia of the system, f is the friction coefficient, and T_m is the mechanical torque.

C. Boost converter model

The equivalent circuit of boost converter is given in Fig. 4 [48], the switch S_1 represents the MOSFET with a constant switching period. The transformer is an ideal type with primary inductance of L_{lk1} and secondary inductance of L_{lk2} while the magnetizing inductance is L_m. The capacitor C_{in} is low pass filter, it can be used to reduce the inductor current to zero when the MOSFET is opened.

The voltage gain of the converter can be written as follows:

$$\frac{V_{out}}{V_{in}} = \frac{n}{1 - D_{S1}} \tag{10}$$

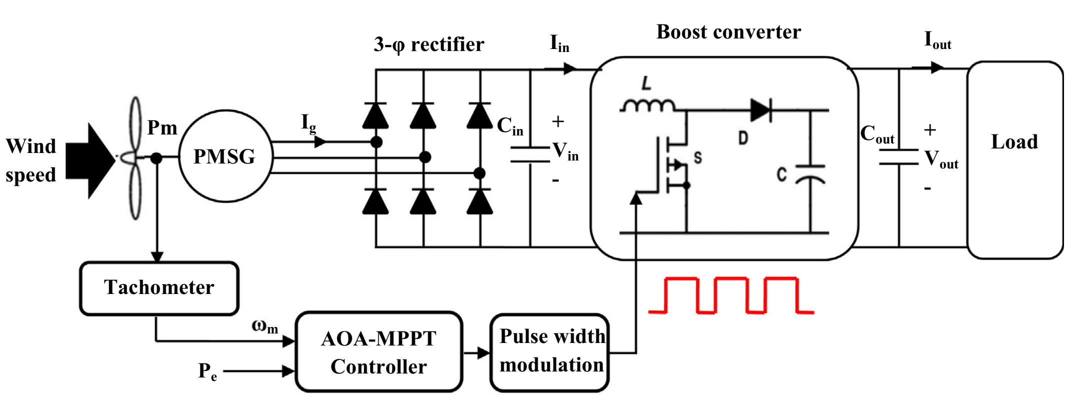


Fig. 1. Construction of wind energy generation system.

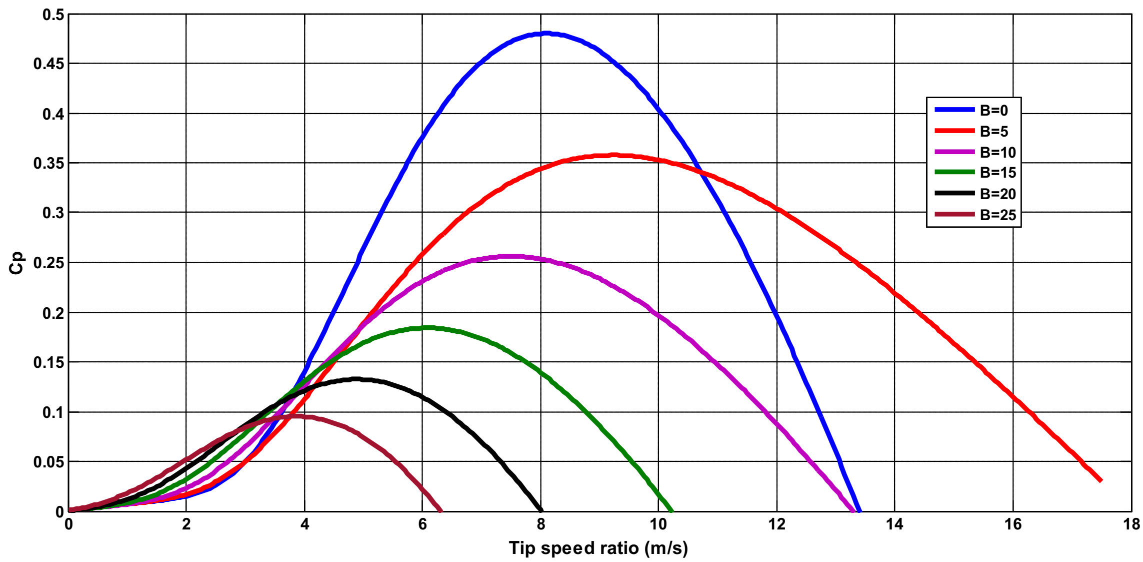


Fig. 2. Variation of C_p to λ at different β.

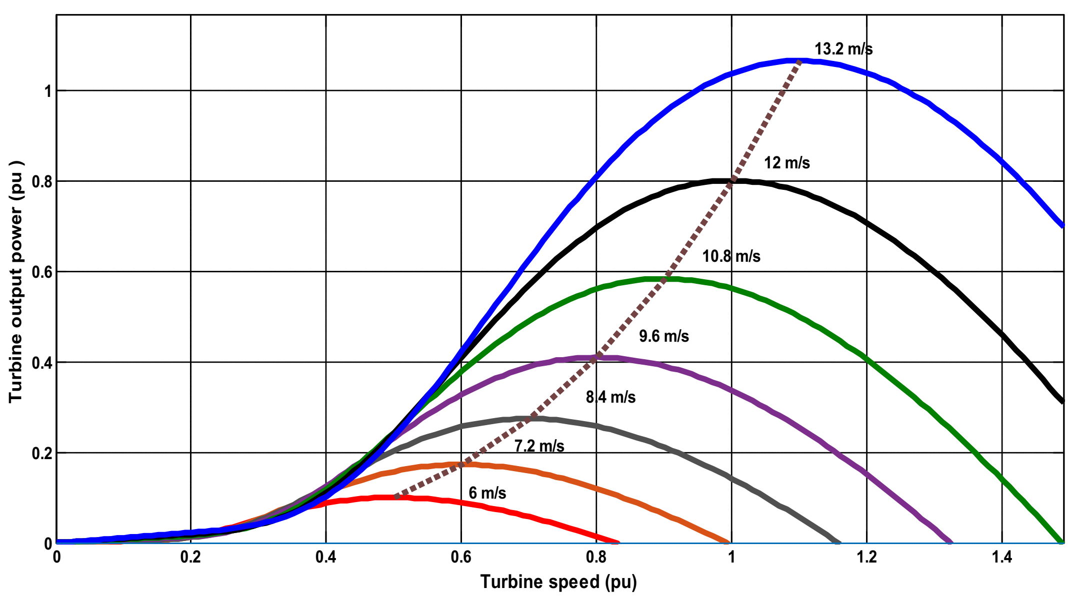


Fig. 3. Mechanical power versus rotational speed.

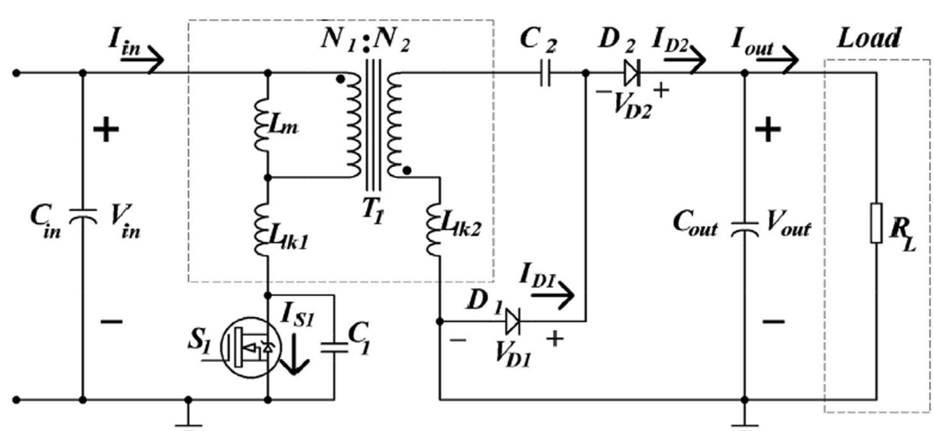


Fig. 4. Equivalent circuit of boost converter [48].

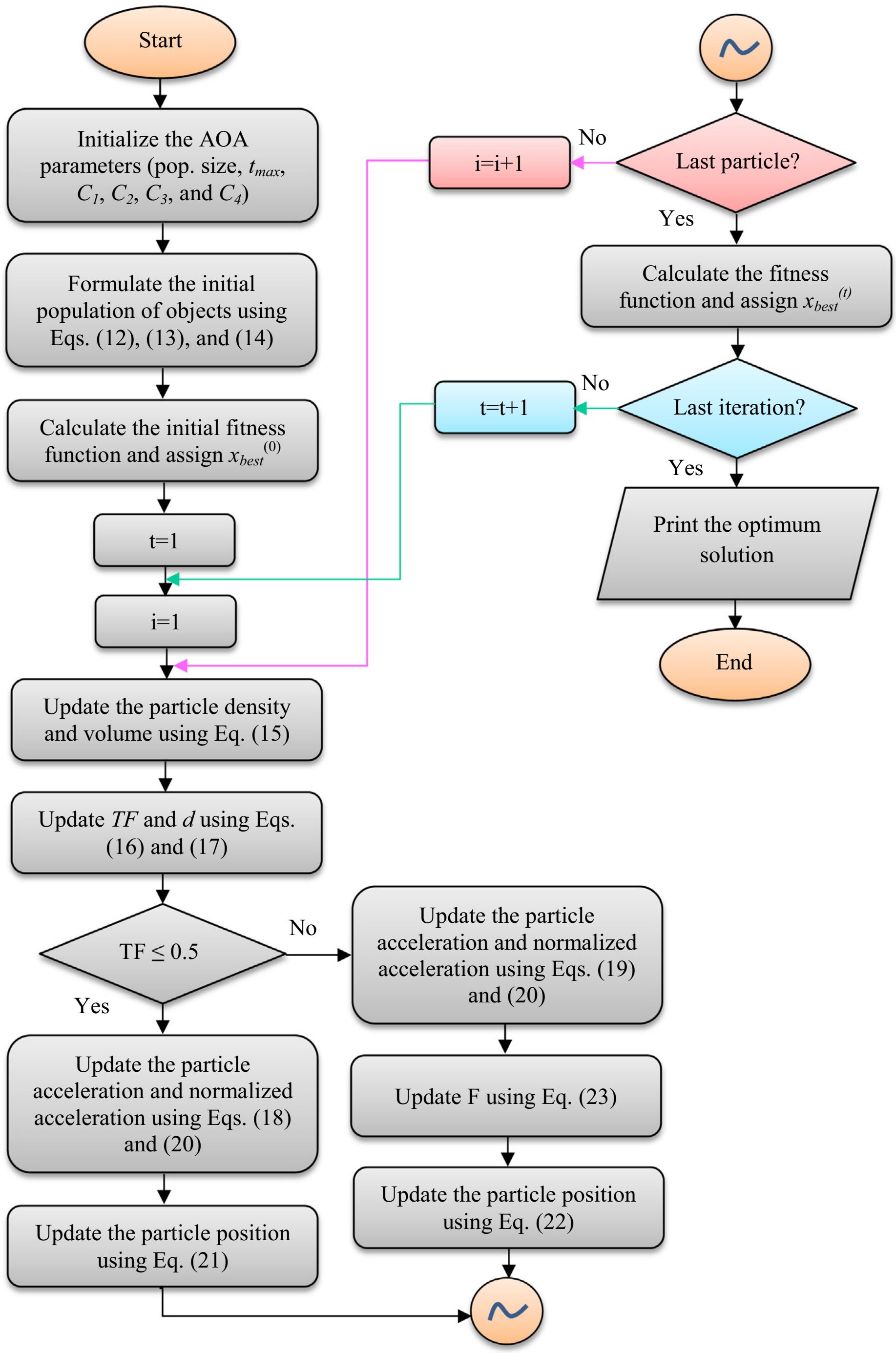


Fig. 5. Flowchart of AOA.

where n is the turns ratio of transformer and D_{s1} is the MOSFET duty cycle. The equivalent input resistance of the converter can be calculated as follows:

$$R_{in} = \frac{(1 - D_{S1})^2}{n^2} R_L \quad (11)$$

where R_L is the resistance of load, the converter duty cycle can control the converter input resistance and the converter input current. In case of increasing the duty cycle, the input resistance of converter is decreased, this action increases the converter input power. Therefore, the output current is increased resulting in decreasing the WT rotational speed. The converter duty cycle can be controlled via MPPT controller to catch the peak power from the wind energy generation system.

4. Archimedes optimization algorithm overview

Archimedes optimization algorithm (AOA) was introduced by *Hashim et al.* [49], the algorithm is motivated from the principle of Archimedes which is considered as law of physics. The Archimedes principle is concerned with the object which partially or completely immersed in the fluid. As there is an upward force (called buoyancy) generated from the liquid on the body, this force

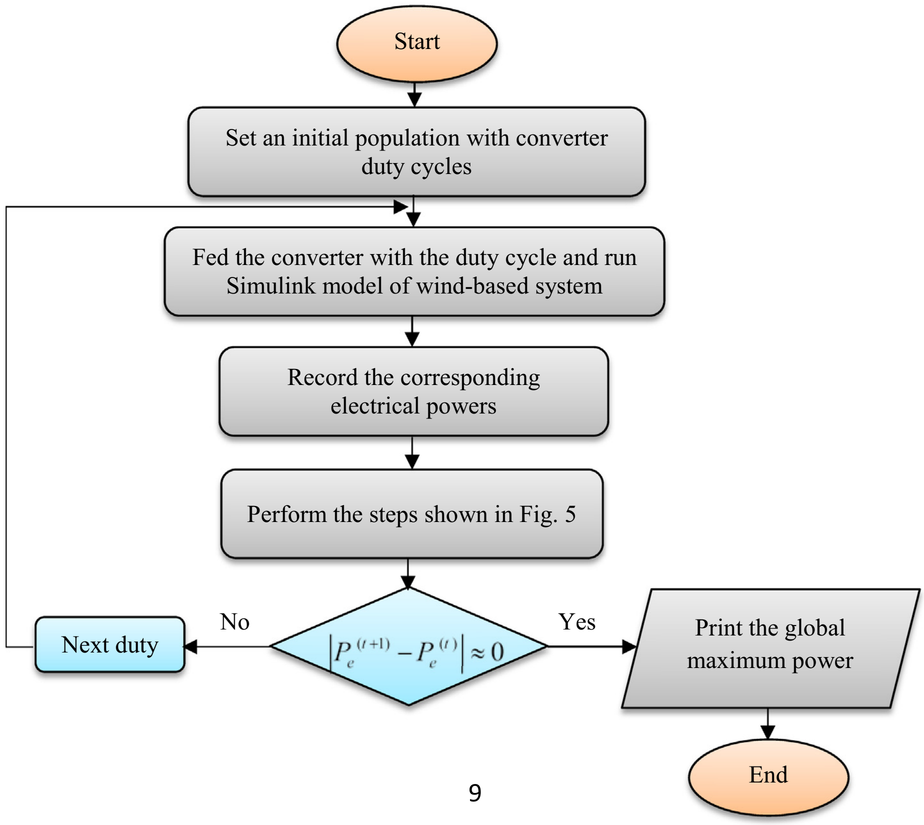


Fig. 6. The proposed steps for designing AOA-MPPT.

is equal to the fluid weight displaced from the body. In AOA, the immersed objects are considered as the population individuals (candidate solutions). The approach begins with initializing a population with objects, moreover the position of each object is initialized in random manner inside the problem search space. Then the corresponding fitness function is calculated. During the iterative process, AOA updates the objects' densities and volumes while their accelerations are updated on the basis of their collisions with neighbor object. The initialization process of all objects is performed using the following formula:

$$O_i = l_i + rand \times (u_i - l_i),\ i = 1, 2, \ldots, N \tag{12}$$

where l_i and u_i are the lower and upper limits of i^{th} object, and N is the number of objects. The volume and density of each object can be initialized as follows:

$$den_i = rand,\ vol_i = rand \tag{13}$$

where *rand* is a vector of *D*-dimension with values in range of [0, 1]. The acceleration of each object can be calculated as follows:

$$acc_i = lb_i + rand \times (ub_i - lb_i) \tag{14}$$

The initial fitness function is calculated and the object with the best fitness is assigned as x^{best}, den^{best}, vol^{best}, and acc^{best}.

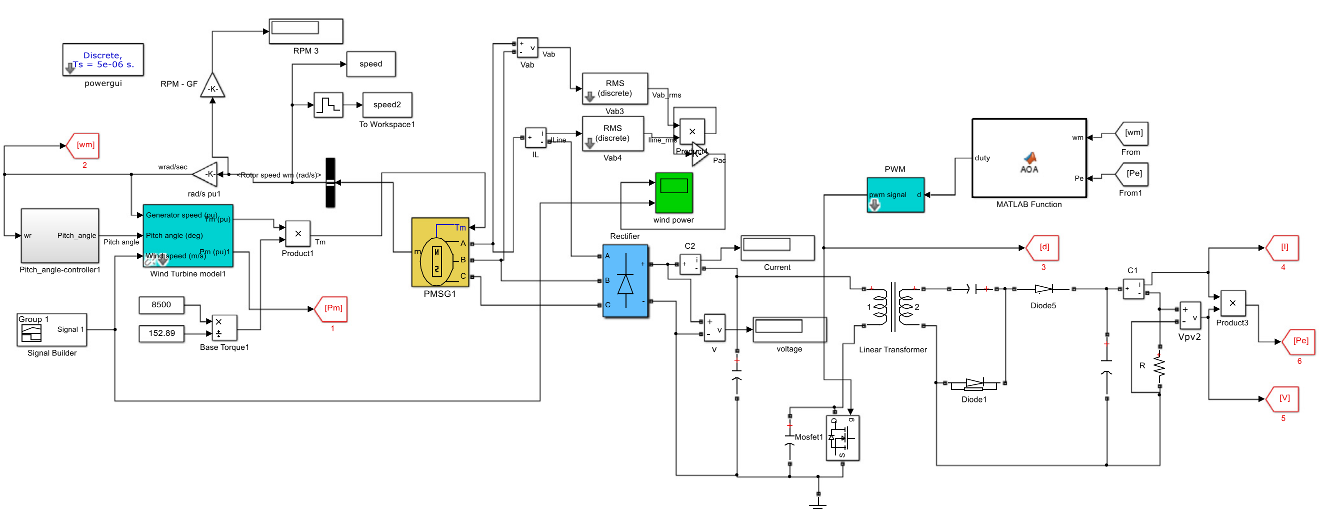


Fig. 7. Simulink model of the proposed AOA-MPPT controller.

Table 1
Specifications of the wind energy system components.

WT		**Boost converter**	
P_{rated}	250 W	C_{in}	680 mF
$V_{cut\text{-}in}$	6 m/s	C_{out}	220 µF
$V_{cut\text{-}out}$	13.2 m/s	C_2	18 mF
β	0°	C_1	1.2 nF
λ^{opt}	8.1	n	10/4
PMSG		L_m	19.14 mH
P_{rated}	1 kW	L_{lk2}	0.031 mH
$V_{rated(L\text{-}N)}$	24 V	L_{lk1}	0.011 mH
R_s	0.05 Ω	R_L	240 Ω
L_s	0.0085H	**Diode rectifier**	
J	0.011 kg.m^2	Forward voltage of diode	0.8 V
Viscous damping	0.001889 N.m.s	Snubber resistance	100 Ω
P	4	Snubber capacitance	0.1 µF
Static friction	0 N.m	R_{on}	1 mΩ

The updating process of i^{th} object's density and volume is performed based on the following formula.:

$$den_i^{t+1} = den_i^t + rand \times \left(den^{best} - den_i^t\right) \tag{15a}$$

$$vol_i^{t+1} = vol_i^t + rand \times \left(vol^{best} - vol_i^t\right) \tag{15b}$$

where t refers to the current iteration and $rand$ is a random number. At the beginning, there is a collision between the objects after which the object tries to reach the equilibrium state. This action is presented in AOA via transfer operator which helps in transformation from exploration phase to exploitation one.

The formula of transfer operator can be written as follows:

$$TF = \exp\left(\frac{t - t_{\max}}{t_{\max}}\right) \tag{16}$$

where t_{max} is the maximum number of iterations. Here, the value of TF is increased gradually with iterations until it reaches to unity. The density decreasing factor is another one that helps AOA for transferring from global to local search, it can be formulated as follows:

$$d^{t+1} = \exp\left(\frac{t - t_{\max}}{t_{\max}}\right) - \left(\frac{t}{t_{\max}}\right) \tag{17}$$

The value of $d^{\,t+1}$ decreases with time, moreover proper assigning of this variable helps in achieving exploration/exploitation balance. The exploration phase is represented by collision between the objects, this phase is considered when the transfer operator is 0.5. The acceleration of i^{th} object at iteration t + 1 is updated by selecting a random material (mr) as follows:

$$acc_i^{t+1} = \frac{den_{mr} + vol_{mr} \times acc_{mr}}{den_i^{t+1} \times vol_i^{t+1}} \tag{18}$$

where den_{mr}, vol_{mr}, and acc_{mr} are the density, volume, and acceleration of random material (mr). The exploitation phase in AOA considers no collision between the objects, this phase is implemented when the value of transfer operator is greater than 0.5. The acceleration of i^{th} object in exploitation phase can be computed as follows:

$$acc_i^{t+1} = \frac{den_{best} + vol_{best} \times acc_{best}}{den_i^{t+1} \times vol_i^{t+1}} \tag{19}$$

Table 2
The optimal results obtained via the proposed AOA and the others at V = 12 m/s.

	CS	GOA [35]	ECPO	The proposed AOA
P_m (W)	80.5449	136.0344	95.955450	136.0343
ω_m (rad/s)	17.5481	29.3676	20.90399	29.3676
duty	0.2000	0.0975	0.1576	0.0911
P_{max} (W)	63.5237	101.1967	78.3044	102.2039
V_{MPP} (V)	123.5	155.8435	137.0878	156.6171
I_{MPP} (A)	0.5145	0.6493	0.57119	0.6526

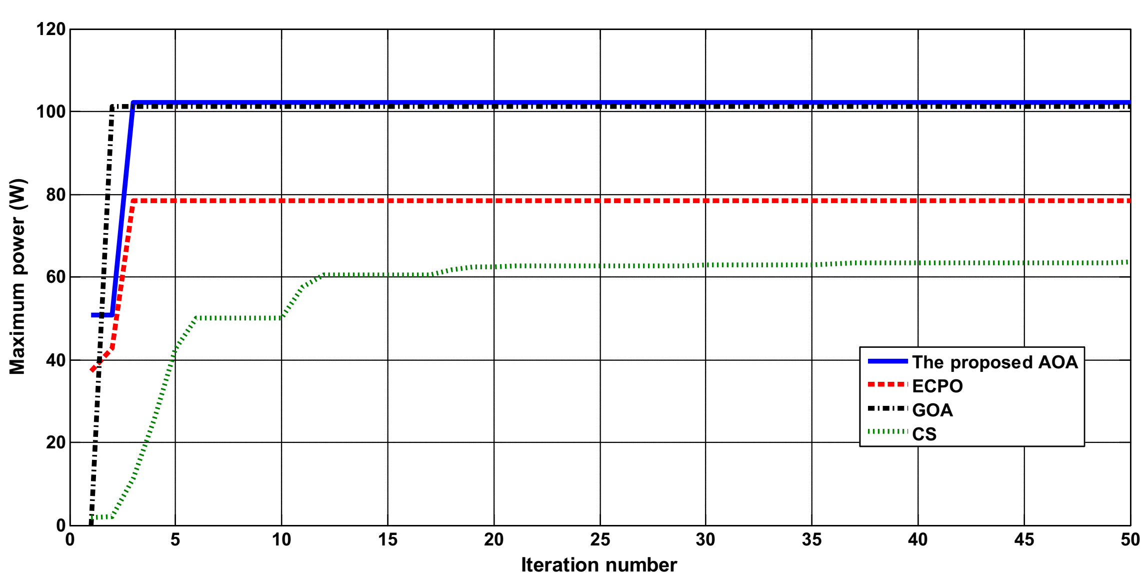


Fig. 8. The variation of maximum power during iterative process.

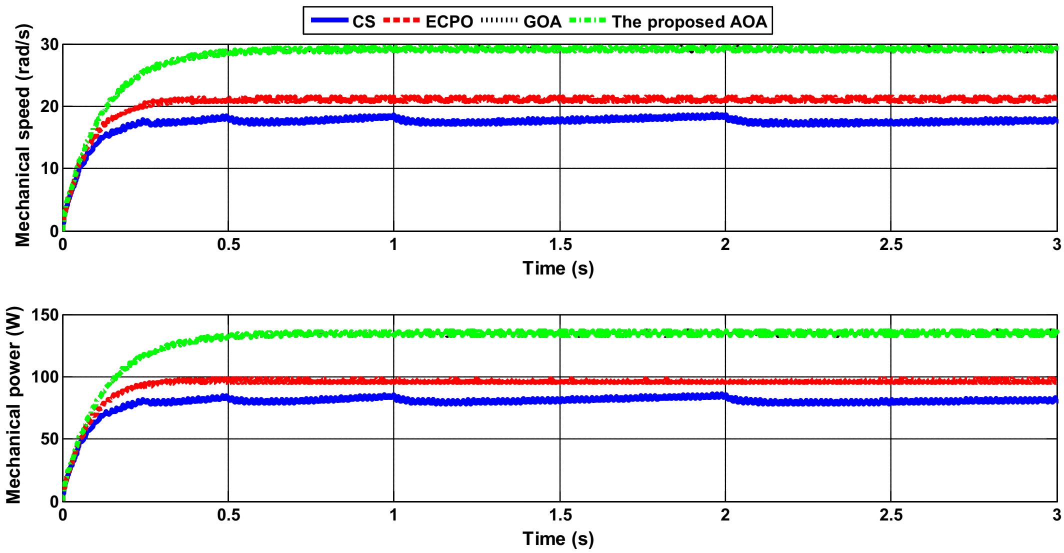


Fig. 9. The time responses of mechanical speed and power at V = 12 m/s.

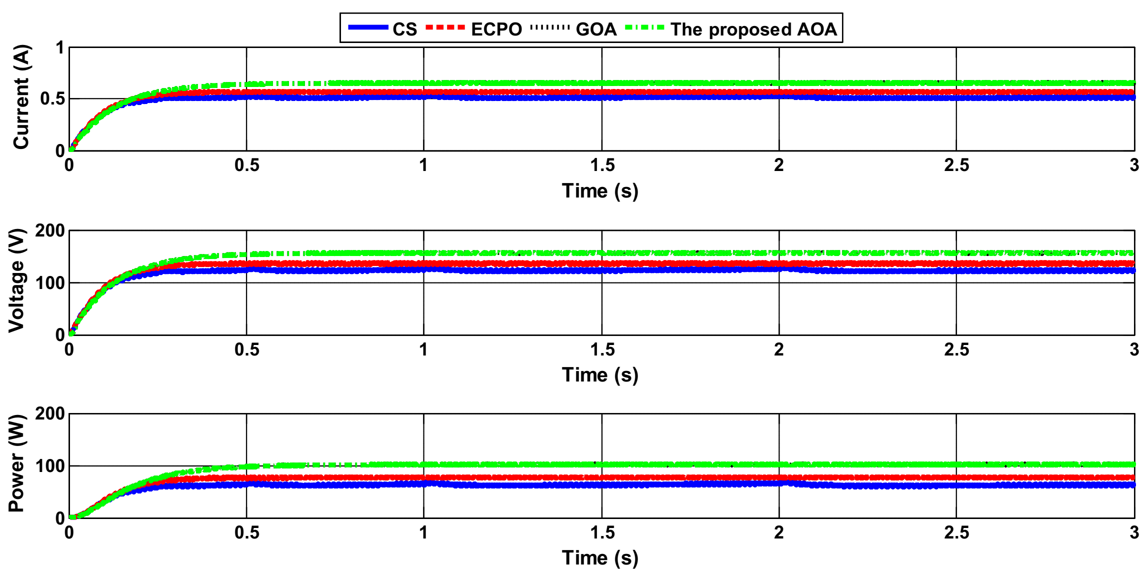


Fig. 10. The time responses of current, voltage, and electrical power at V = 12 m/s.

where den_{best}, vol_{best}, and acc_{best} are the best object density, volume, and acceleration respectively. It is important to normalize the acceleration of each particle, this determines the step percentage that each particle will change. The normalized acceleration can be written as follows:

$$acc_{i-norm}^{t+1} = u \times \left(\frac{acc_i^{t+1} - \min(acc)}{\max(acc) - \min(acc)} \right) + l \tag{20}$$

where l and u are the normalization range, they are assigned as 0.1 and 0.9 respectively. When the object is far away from the global optima, the value of acceleration will be high, in this case exploration phase is conducted else exploitation phase is presented.

The position of i^{th} particle is updated in exploration phase using the following formula:

$$x_i^{t+1} = x_i^t + C_1 \times rand \times acc_{i-norm}^{t+1} \times d \times \left(x_{rand} - x_i^t \right) \tag{21}$$

On the other hand, the updating process of particles' positions during the exploitation phase can be presented as follows:

$$x_i^{t+1} = x_i^t + F \times C_2 \times rand \times acc_{i-norm}^{t+1} \times d \times \left(T \times x_{best} - x_i^t \right) \tag{22}$$

where C_1 and C_2 are constants defined by the user, T is a parameter that depends on the transfer operator ($T = C_3 \times TF$), C_3 is a constant value, x_{best} is the position of the best particle, and F is the flag employed to change the particle's motion direction. The value of F can be determined using the following formula: $F = \begin{cases} +1 & P \leqslant 0.5 \\ -1 & P > 0.5 \end{cases}$ (23)where the value of P is assigned randomly by the user. Finally, the fitness function is computed at the updated particles' positions and then the best solution is recorded. Fig. 5 shows the flowchart of AOA.

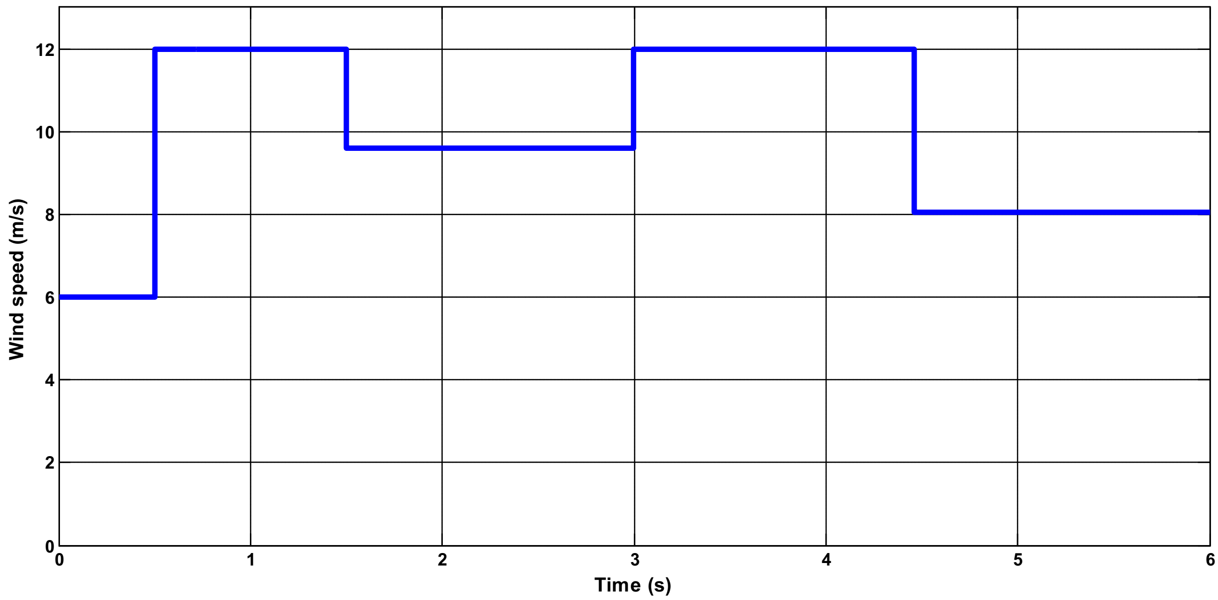


Fig. 11. Time response of variable wind speed considered in scenario (2).

Table 3
The optimal results obtained via AOA in comparison to GOA in scenario (2).

Time interval (sec.)	[0–0.5]		[0.5–1.5]		[1.5–3]		[3–4.5]		[4.5–6]	
	AOA	GOA	AOA	GOA	AOA	GOA	AOA	GOA	AOA	GOA
P_m (W)	8.7363	8.603	131.3387	135.9	55.617	55.83	135.6637	136.5	28.2696	18.24
ω_m (rad/sec.)	7.6135	7.747	28.4347	29.3	18.9225	18.65	29.29498	29.45	13.6855	8.851
P_{max} (W)	6.3819	6.217	102.136	101.7	41.2778	41.2	102.2028	102.2	18.8562	13.22
V_{MPP} (V)	39.1364	37.68	156.2965	156	99.5323	99.44	156.765	156.6	67.2717	56.22
I_{MPP} (A)	0.1631	0.159	0.6535	0.651	0.4147	0.414	0.6519	0.652	0.2803	0.233

5. The proposed optimization formula

The designing methodology of MPPT installed with wind energy system followed in this paper is implemented as optimization problem, the considered fitness function to be maximized is the electrical power extracted from the wind energy system. The objective function is formulated as follows:

$$Maximize\, P_e(t) = \left(\frac{V_{out}(t)}{n} \times (1 - D_{S1}) * I_{in}(t)\right) \tag{24}$$

where $V_{out}(t)$ is the load terminal voltage at instant t and $I_{in}(t)$ is the input current to converter at instant t. The power extracted from the wind energy system can be controlled via adapting the duty cycle D_{S1}. The corresponding constraint is related to the duty cycle as follows:

$$D_{s1,\min} \leqslant D_{s1} \leqslant D_{s1,\max} \tag{25}$$

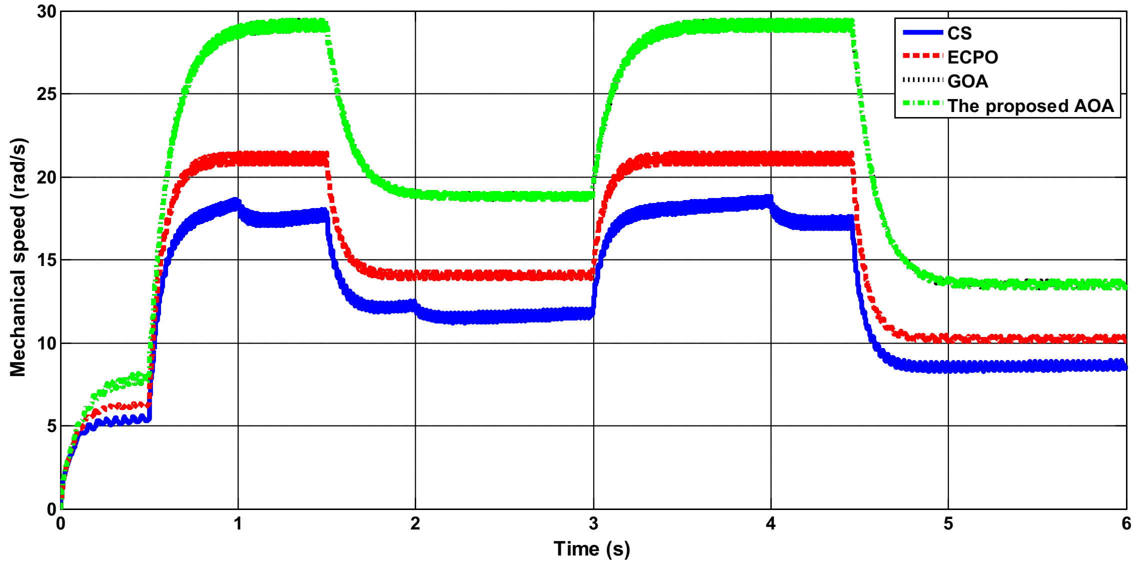
where $D_{s1,\min}$ and $D_{s1,\max}$ are the lower and upper bounds of the MOSFET duty cycle, they are assigned as 0 and 1 respectively. The authors selected a recent metaheurestic optimizer of Archimedes optimization algorithm (AOA) to represent the MPPT installed with the system. AOA is selected as it is simple and straightforward in implementation, moreover it has less controlling parameters. Furthermore, it has exploration/exploitation balance that helps the algorithm to extract the global optima. Fig. 6 shows the proposed steps followed in the proposed AOA to design the MPPT installed with wind energy system. The proposed methodology incorporated AOA begins by initializing a population with converter duty cycles based on the upper and lower limits defined by the user. After that, each duty cycle is fed to the converter MOSFET, the corresponding electrical power is recorded as $P_e^{(t)}$. The iterative process given in Fig. 5 is implemented and the obtained power is recorded as $P_e^{(t+1)}$. The duty cycle is updated based on Eqs. (21) and (22) when $P_e^{(t+1)}$ is greater than $P_e^{(t)}$. The iterative process is continued until the error between the current power and that obtained in the previous iteration converges to zero. Finally, the global maximum power is printed.

6. Results and discussions

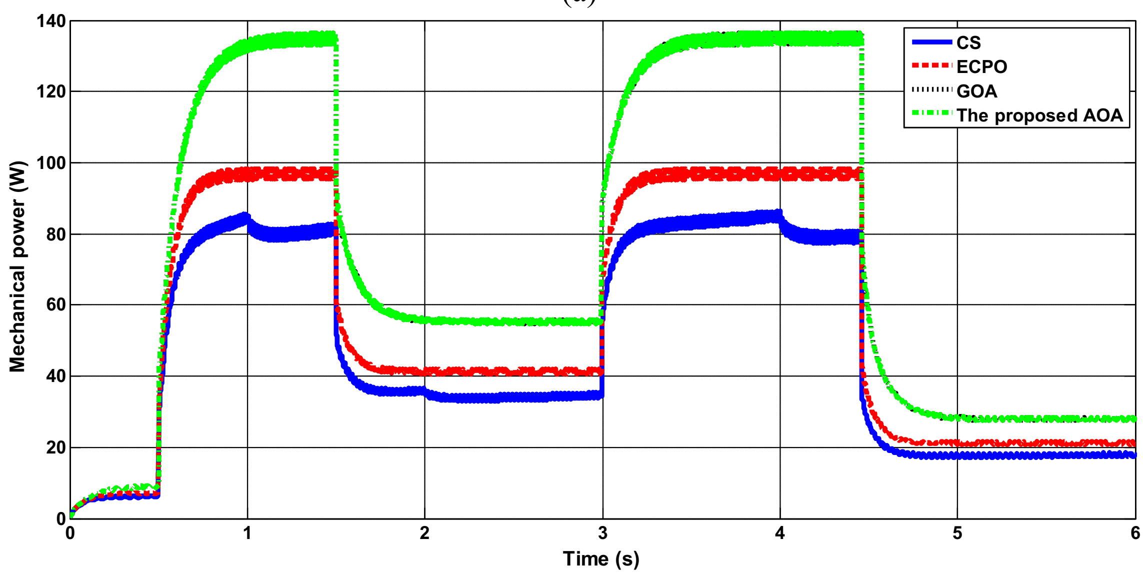
The Simulink model of the proposed AOA-MPPT controller with wind energy generation system is constructed as shown in Fig. 7. AOA is programmed in Matlab function, the mechanical rotational speed and electrical power are fed to the AOA-MPPT controller while the duty cycle is the output. Three operating conditions are studied in this work considering constant, variable, and real wind speeds. The system specifications are given in Table 1, the population size of AOA is selected as 4 and the maximum iteration is assigned to 50. All optimizers utilized in this work are implemented for 20 runs and the one with the best fitness function is selected as the final solution.

A. Scenario (1): Constant wind speed

The first scenario studied in this work is conducted at fixed wind speed with a value of 12 m/s. The proposed AOA is implemented and the obtained results are compared with cuckoo search (CS), grasshopper optimization algorithm (GOA) [35], and electric



(a)



(b)

Fig. 12. The time responses of (a) WT speed, (b) WT mechanical power, (c) current, (d) voltage, and (e) electrical power at scenario (2).

charged particle optimization (ECPO). The optimal results at such case are given in Table 2.

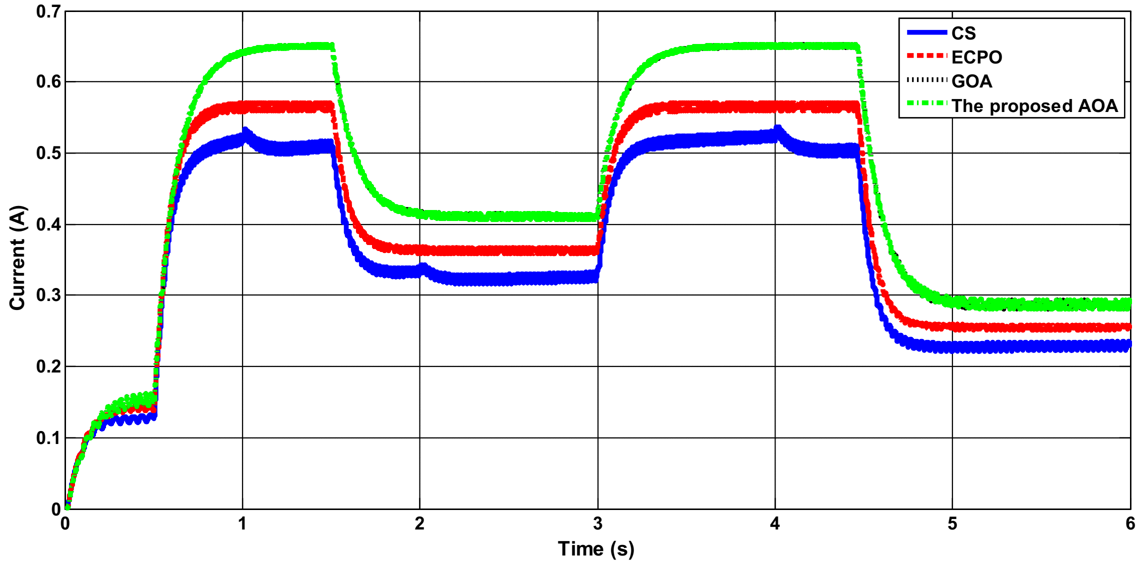
The proposed AOA outperformed CS, GOA [35], and ECPO achieving maxi mum electrical power of 102.2039 W at duty cycle of 0.0911 fed to the converter MOSFET. GOA comes in the second rank achieving a maximum power of 101.1967 W after feeding the converter by duty cycle of 0.0975. CS and ECPO based algorithms achieved maximum powers of 63.5237 W and 78.3044 W at duty cycles of 0.2 and 0.1576 respectively. This confirms that, both CS and ECPO fall in local optima. Fig. 8 shows the variation of maximum power (fitness function) during iterative process of all studied optimizers.

The time responses of WT rotational speed and mechanical power obtained via all studied optimizers are given in Fig. 9 while the variations of current, voltage, and electrical power with time are given in Fig. 10. The obtained curves confirm the superiority of the proposed AOA compared to CS, GOA, and ECPO.

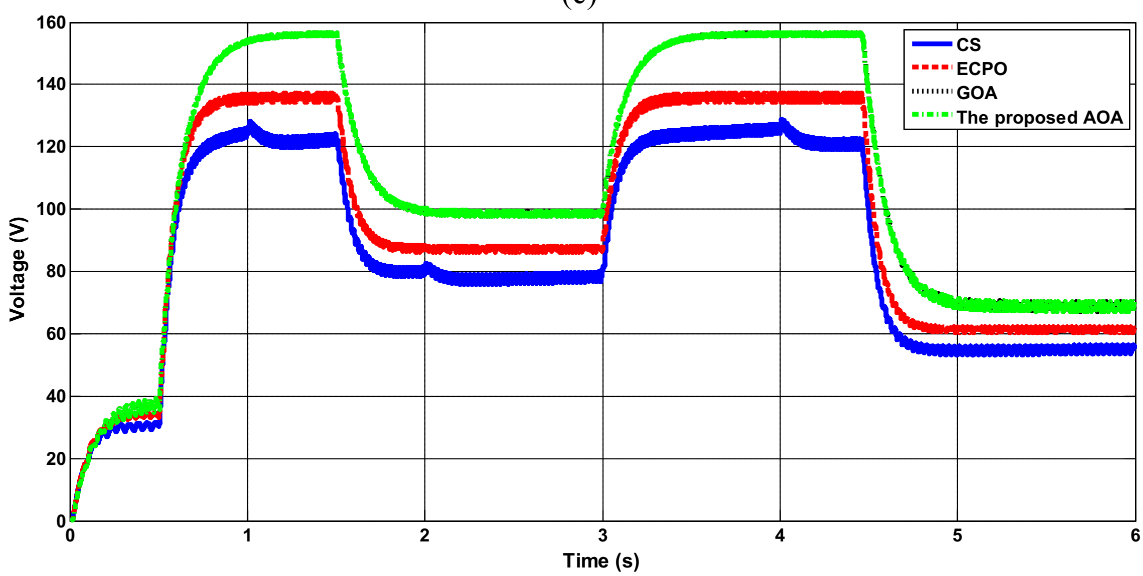
B. Scenario (2): Variable wind speed

It is important to invetsigate the constructed MPPT vi the proposed AOA under operating the wind turbine at variable wind speed. Five variations are considered in the wind speed as shown in Fig. 11.

The proposed AOA is implemented in this case and the obtained results are tabulated in Table 3 in comparison with those obtained via GOA [35]. As the reader see, in the second interval, the proposed AOA-MPPT extracted power from the wind generation system of 102.136 W while GOA achieved 101.7 W. The proposed AOA outperformed GOA approach implemented by the authors in



(c)



(d)

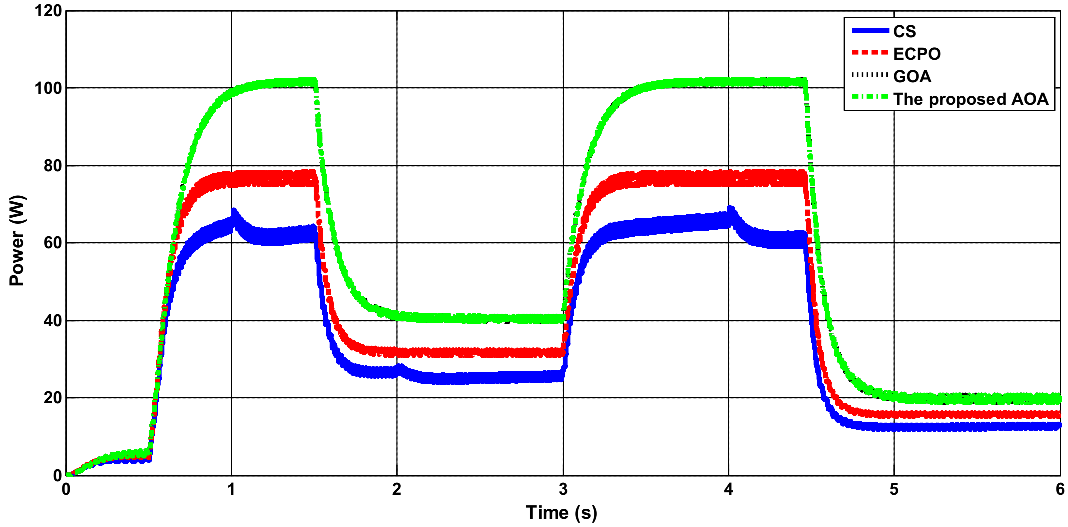
Fig. 12 (*continued*)

[35] for all time intervals. The time responses of rotational speed, mechanical power, current, voltage, and electrical power obtained from all optimizers are shown in Fig. 12.

The proposed AOA-MPPT controller achieved great performance in catching the peak power from the wind generation system at variable wind speed.

C. Scenario (3): Practical case study

It is important to investigate the proposed tracker for system installed at different sites in the Kingdom of Saudi Arabia with different weathers. The selected locations are Sakaka (29.878° latitude and 40.1043° longitude) which is located at the northern region of the kingdom, Riyadh (24.7742° latitude and 46.7385° longitude) which is the capital of Saudi Arabia, Jeddah (21.5433° latitude and 39.17277° longitude) which is located in Hejaz region of Saudi Arabia, and Jizan (16.90968° latitude and 42.5679° longitude) at the south of the Kingdom. The real data of wind speed at these locations are collected with the aid of NASA [50], the considered time interval is selected as six months starting from the first of August 2020 to 31 January 2021. The collected measured data of wind speed for the selected locations are shown in Fig. 13. The proposed AOA is implemented in comparison to ECPO, the obtained results for Sakaka, Riyadh, Jeddah, and Jizan are recorded in Table 4. For Sakaka city, the proposed approach succeeded in extracting maximum power of 12.7988 W and average daily power of 0.927 W. while the ECPO based MPPT achieved 9.8654 W maximum power and 0.75029 W average daily power. Similarly, the AOA-MPPT achieved the best results for Riyadh, Jeddah, and Jizan. The proposed MPPT achieved great performance for operation under different weathers compared to ECPO based tracker.



(e)

Fig. 12 (*continued*)

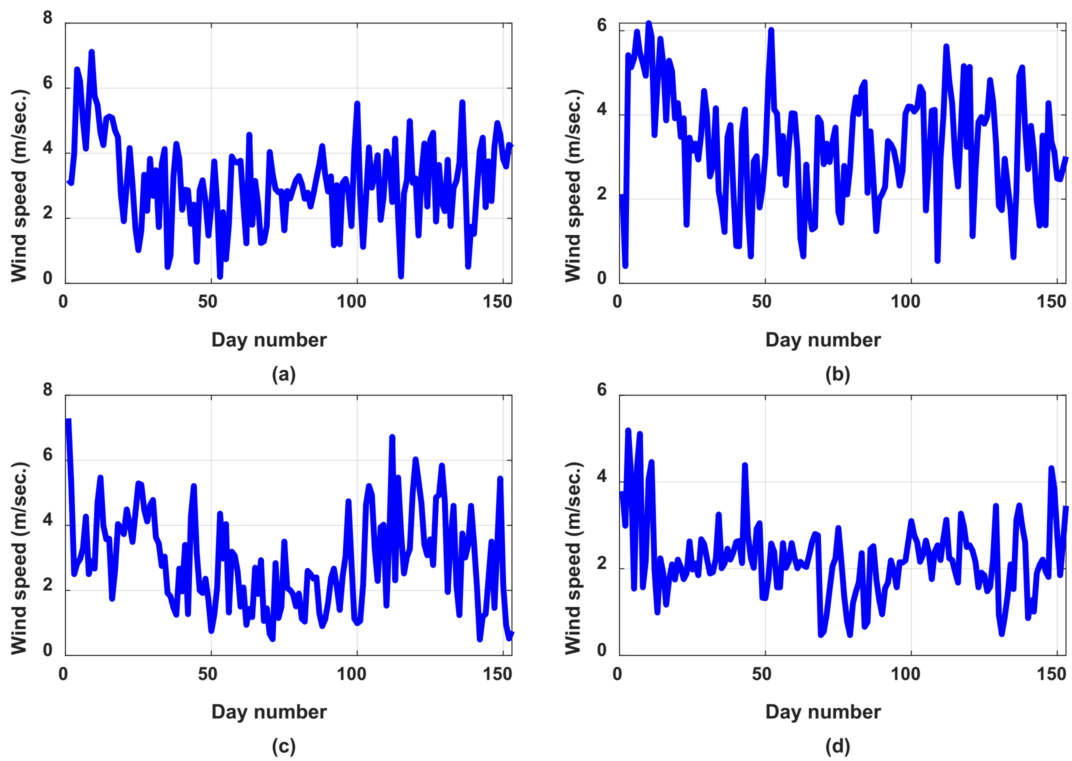
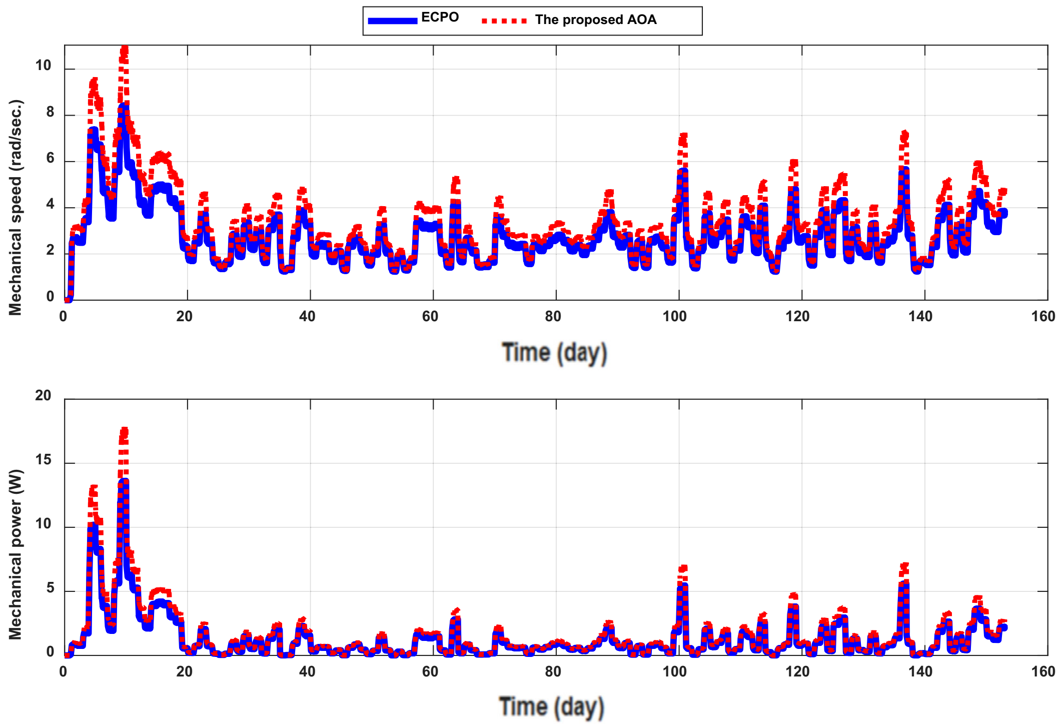


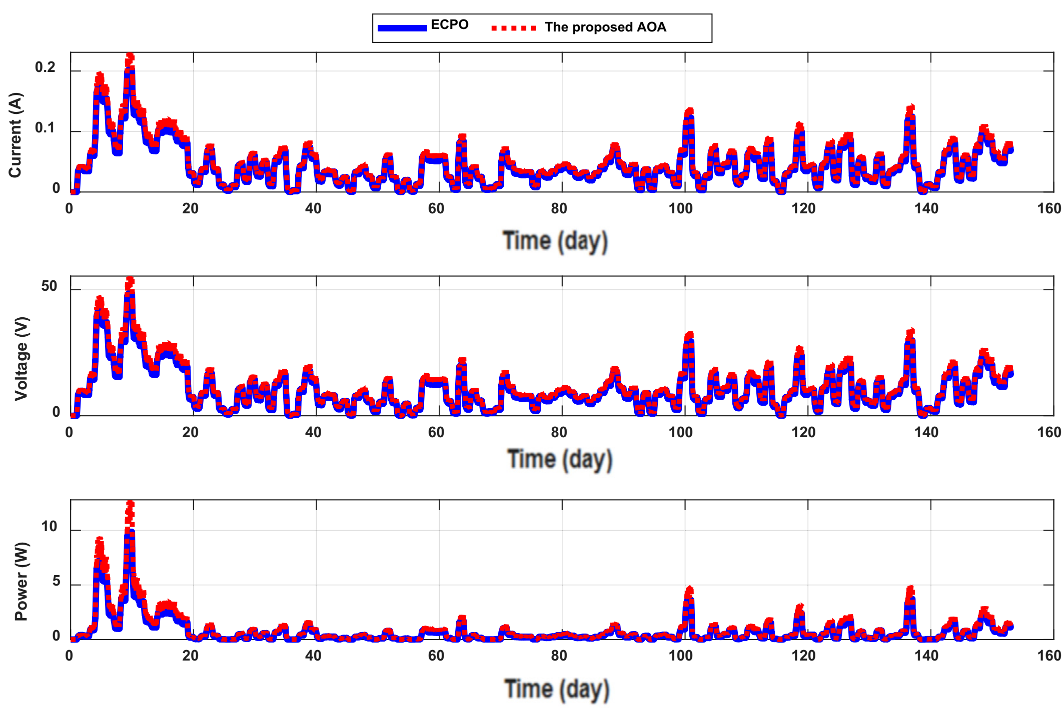
Fig. 13. The measured wind speed for (a) Sakaka, (b) Riyadh, (c) Jeddah, and (d) Jizan.

Table 4
The optimal results obtained via AOA in comparison to ECPO in scenario (3).

	Sakaka		Riyadh		Jeddah		Jizan	
	ECPO	AOA	ECPO	AOA	ECPO	AOA	ECPO	AOA
P_m (kW)	1.3395	1.6535	1.5084	1.8681	1.3032	1.6115	0.4394	0.5171
ω_{m_av} (rad/sec.)	2.7981	3.3675	2.9558	3.5826	2.6978	3.2304	1.9991	2.2799
P_{max} (W)	9.8654	12.7988	5.6231	7.3911	10.8367	14.0281	2.8191	3.7161
P_{av} (W/day)	0.75029	0.9270	0.8553	1.0586	0.7451	0.9180	0.1838	0.2279



(a)



(b)

Fig. 14. Time responses of (a) rotational speed and mechanical power, (b) current, voltage, and power for wind generation system installed in Sakaka city.

The time responses of the WT rotational speed, mechanical power, current, voltage and electrical power obtained via the proposed AOA and ECPO for Sakaka, Riadh, Jeddah, and Jizan are shown in Figs. 14-17, respictevly. The curves confirm the superirity of the proposed approach in all studied locations.

The constructed MPPT via AOA robustness is confirmed in extracting the maximum power of wind generation system installed in different locations in Saudi Arabia.

The obtained results in all studied scenarios confirmed the superiority and reliability of the constructed tracker via the pro-

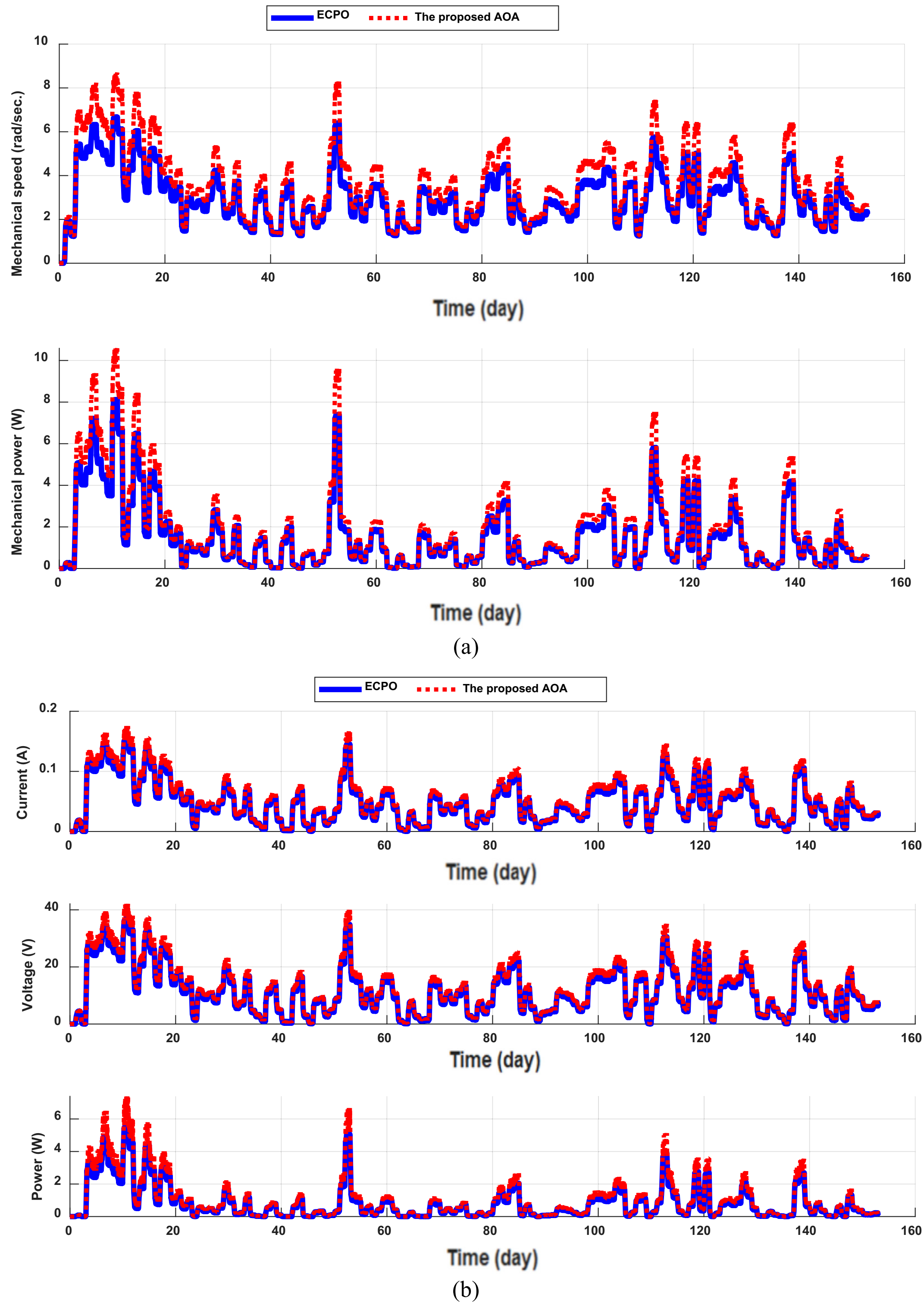


Fig. 15. Time responses of (a) rotational speed and mechanical power, (b) current, voltage, and power for wind generation system installed in Riyadh city.

posed AOA based approach. Therefore, the authors recommend the installation of AOA-MPPT with wind energy generation system as it is able to work in online mode.

7. Conclusion

This paper presented a novel application of Archimedes optimization algorithm (AOA) to implement the MPPT installed with wind energy generation system to improve its performance. The presented generation system comprises WT connected to PMSG. The generator output is converted to DC using 3-phase rectifier which its terminals are connected to boost converter to control the DC power required by the load. The proposed AOA controls the duty cycle of the converter MOSFET such that the output power from the wind energy generation system is maximized. The proposed approach is investigated under operating the wind energy

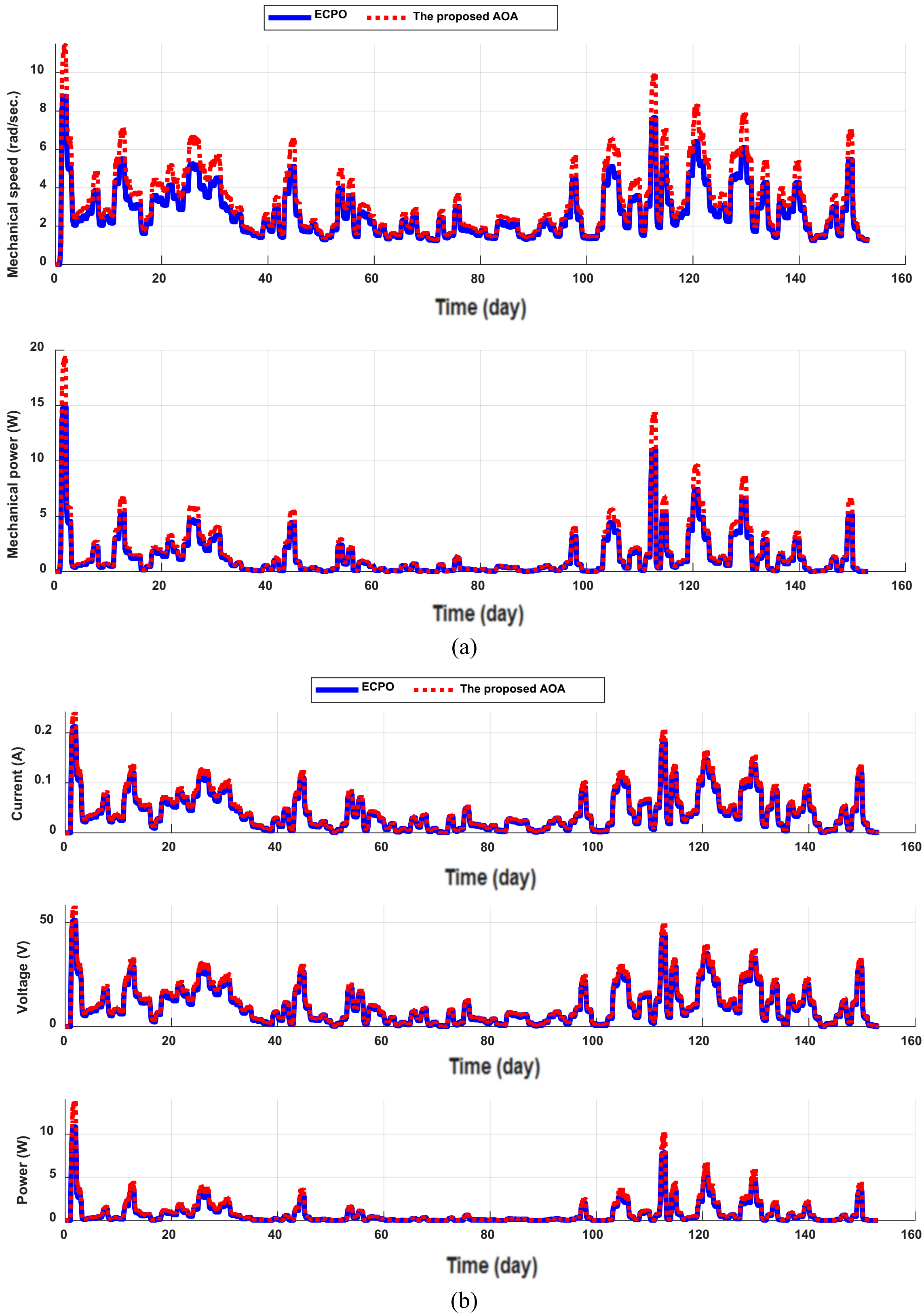


Fig. 16. Time responses of (a) rotational speed and mechanical power, (b) current, voltage, and power for wind generation system installed in Jeddah city.

system at fixed, variable, and real recorded wind speeds. Real data of wind speed are recorded at different regions in Saudi Arabia which are Sakaka, Riyadh, Jeddah, and Jizan and the proposed tracker is investigated. The results obtained via the proposed approach are compared with those obtained via cuckoo search (CS), grasshopper optimization algorithm (GOA), and electric charged particle optimization (ECPO). Regarding to the scenario of fixed wind speed operation, the AOA-MPPT controller succeeded

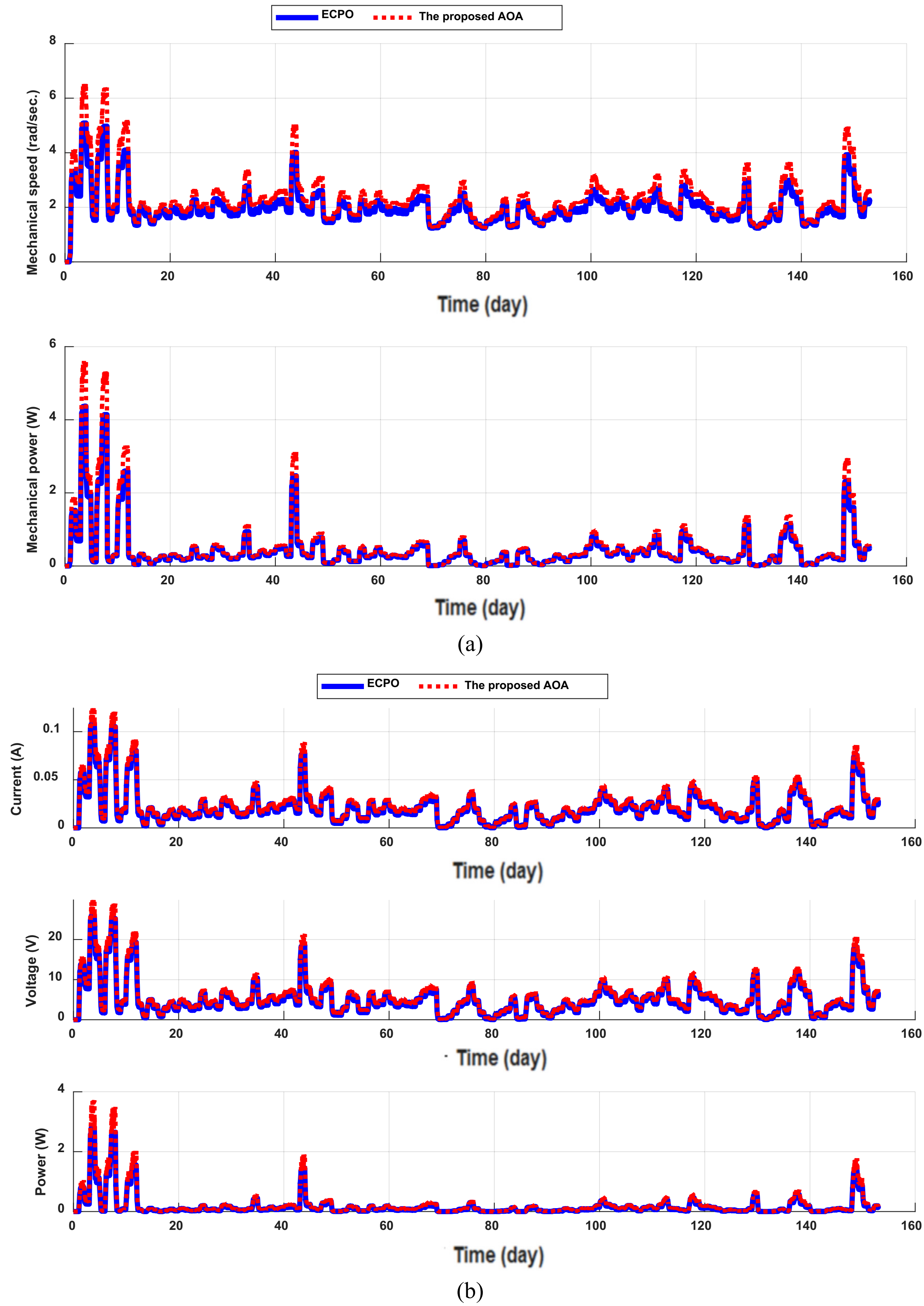


Fig. 17. Time responses of (a) rotational speed and mechanical power, (b) current, voltage, and power for wind generation system installed in Jizan city.

in extracting maximum power of 102.2039 W at duty cycle of 0.0911 while GOA achieved maximum power of 101.1967 W. For operation under variable speed, 102.136 W is extracted via the proposed AOA-MPPT controller and 101.7 W is obtained by GOA-MPPT controller. In the practical case study, the proposed AOA extracted 12.7988 W for Sakaka city while 9.8654 W is obtained via ECPO. The results confirmed the robustness of the proposed AOA-MPPT controller in achieving the best performance of wind energy generation system as it outperformed all considered optimizers. The proposed algorithm shall be used to solve several optimization problems for other renewable energy systems and smart grid in the near future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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